COMPUTER AIDED SIMULATION OF THE DYNAMICS OF A MANIPULATOR

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CERTIFICATE

Certified that the present work entitled 'Computer Aided Simulation of the Dynamics of a Manipulater' has been carried out by Sri Madhu Shekhar, C. under the supervision of Dr. B.Sahay, and has not been submitted elsewhere for a degree.

Dr. B.Sahay has gone abroad to Canada for three months, and has authorised me to submit the certificate on his behalf and to look after the viva of Sri Madhu Shekhar.

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Various other people have contributed in various ways towards this project : The Computer Centre, Library, and Mechanical Department staff, and of course my friends.

6/7/85

C.MADHU SHEKHAR

CONTENTS

LIST OF SYMBOLS

N	Number of links of an Articulate Mechanical System (AMS)
L_i	ith link of the AMS
T_i	ith joint of the AMS
G_i	Centre of gravity of L_i
C_i	Body fixed coordinate frame of L_i
O_i	Origin of C_i
a	Link length
α	Link twist
θ	Joint angle
u	Joint distance
ρ	Position vector of the centre of gravity of the link
m	Mass of the link
J	Inertia tensor of the link
A	Transition block matrix
B	Jacobian block matrix
q	Internal coordinate vector
X	External coordinate vector
P	Drive vector
F	Force block vector
M	Moment block vector

ABSTRACT

Dynamic performance is one of the most significant factors in the design of manipulators particularly for fast and accurate robots recently developed.

Until the end of the last decade, the choice of the manipulator , the actuator and the control system units was a subject of free speculation, frequently based on experience but lacking any systematic method. Hence the need for developing certain criteria and procedures for a systematic design of the manipulator. In the design phase, there is no efficient means except simulation to investigate and evaluate the highly non linear and coupled systems. The aim of this work is to create a software tool for the simulation of all the dynamical values and characteristics of manipulator operations in a particular task execution and thus permit a fast evaluation of a great number of different configurations.

CHAPTER I

INTRODUCTION

In 1920, the Czech writer Carel Kapek wrote a collective drama entitled R.U.R (Rossum's Universal Robot) and with its translation the word Robot entered the English vocabulary.

For half a century the word Robot appeared on the pages of science fiction stories and novels. Issac Assimov coined the name of the trade, ' Robotics ', and provided us Roboticists with an ethic. These terms were later adopted by the scientific and technical community.

The robot may be defined as a class of technical systems which imitate or substitute human locomotion or intellectual function. The Robot Institute of America gives a more precise and technical defination: ' A robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialised devices, through variable programmed motions for the performance of a variety of tasks'.

Although the size, structure, function and architecture of robots vary widely, all of them have certain essential features:

a) Manipulator

b) Controller

c) Actuators

d) Sensors

Robots posses several specific qualities in both a mechanical and a control sense. In the mechanical sense, a feature specific to manipulation robots is that they are open chain'active mechanisms', in contrast to conventional mechanisms in which motion is produced primarily by the so called kinematic degrees of freedom. Also, they have a versatile structure, ranging from open to closed, from one to some other kind of boundary conditions. From a control viewpoint, robot systems represent, multi variable and essentially non-linear automatic control systems. A manipulation robot is also an example of dynamically coupled system, and the control task itself is a dynamic task. A further feature is the redundancy reflected in an excess of the degrees of freedom for producing certain functional movements of articulated mechanical system. While it permits a greater mechanical flexibility in task performance, it complicates the control system by introducing optimising procedures for solving the problem of system redundancy. The surplus dof are used to satisfy special additional requests.

A list of the uses of robots is impressive. Robots have been used for operation in dangerous environments, in oceanography, space exploration, agriculture, medicines, etc. In industry, their scope is virtually boundless. The development of automatically controlled industrial robots has witnessed three generations : Programmable, Supervisory Controlled, and Artificial Intelligence robots. The boom which we observe today in the sphere of industrial robots is not a mere tribute to vogue. These ' steel collar workers' are now handling, transforming, assembling and dissembling parts, tools and specialised systems. In contrast to hard automation, robots represent ' soft ' automation - flexible, neither product, nor operations, nor industry limited, and immune to obsolescence.

The distance separating Carel Kapek from Cybernetics was covered in a quarter of a century. The next twenty five year period built the foundations of what seemed pure fantasy. In this quarter we are witnessing a quantitative accumulation and a qualitative leap in the field of Robotry.

LITERATURE REVIEW

Although Robotics is a multidisciplinary field, incorporating the results of numerous scientific and engineering disciplines, two major areas can be identified: areas

involving mechanisms and areas involving control systems. In this work, we have confined ourselves only to the former: in particular to the dynamics of manipulators.

The first work in the field of dynamics of spatial mechanisms was published by N.G. Bruyevich [[redacted]] as far back as in 1937.

In 1963, H.J. Fletcher, L. Rongved and E.Y.Yu [[redacted]] studied the motion of a satellite composed of two rigid bodies, connected by a universal joint, under the load due to gravitation.

In 1965, W.W. Hooker and G. Margulien [2] inspired by the preceeding work, studied the general case, where N+1 bodies are connected by means of joints with one or two rotational degrees of freedom. Although this method was a significant advance in that it used matrix formalism, it was not able to obtain the matrices as functions of system state.

R.E. Roberson and J. Wittenburg [[redacted]] in their approach have defined the system of bodies as a graph, whereby the elaborated and known graph properties are used.

The method of W.W. Hooker [[redacted]] provides a new possibility of eliminating constraints but presents a serious problem in deriving the motion equations.

The method of P.W. Likins [[redacted]] proposed in 1971, is a more direct application of the preceeding method. Moreover, without reducing the problem's generality, it simplifies the numerical designation of the links in the chain.

J Wittenburg [4] generalised the method to systems having the structure of a topological branch whose joints permit r revolute dof's and t linear dof's. It does not however, include fully closed chains, nor does it offer an explicit matrix procedure for obtaining the equations.

In 1968, J.J. Uicker [3] proposed a method based on Lagrange's equations for the study of dynamical behaviour of joint connected systems of arbitrary structure. The method is sufficiently general to enable motion equations to be simulated on a computer. To overcome certain deficiencies in this method, M. Renaud [[redacted]] proposed a method based on matrix calculus. In 1977, J. Zabala [5] proposed an algorithm based on M. Renaud's method for automatically formulating motion equations.

In 1974, E.P. Popov et al [[redacted]] proposed an algorithm for solving the inverse problem based on the Gauss principle of numerical minimisation. The direct problem is solved from the necessary conditions of minimum.

In 1979, M.Vukobratovic and V. Potkonjak [[redacted]] proposed a method based on Appel's equations, and is computer oriented to a great extent.

All the methods based on the general theorem of dynamics (except the method of P.W. Likins) are based on direct enumeration. However for an efficient computer solution, a recursive formulation is desirable. The methods using Newton's and Euler's methods are in principle complex due to the complexity of eliminating the constraints by forces and moments. Lagrangian equations provide the possibility of directly regarding the equations as functions of system control inputs. However, the inherent unsuitability of applying these equations lies in the need to calculate partial derivatives of Lagrangian functions.

OUTLINE OF THE PRESENT WORK

Modelling of the dynamics of Open Chain Active Mechanisms (OCAM) is a central point in the modern approach to manipulator design for two main reasons. One is connected with dynamic control, and the second is the development of procedures for optimal design of manipulators.

As a rule, the methods for the dynamic analysis of active mechanisms use generalised coordinates. However,

in practice such a solution is insufficient, because one needs to consider the so called functional robot motion. This is a motion satisfying certain practical demands. It is therefore necessary to obtain drives producing these functional motions. Considerations of functional dynamics are closely connected with control and conversly. Hence, the term Dynamic Control, meaning, control based on detailed knowledge of the system dynamic characteristics has been introduced.

OCAM have complicated behaviour including interaction among multiple joints, non linear effects, and varying inertia depending upon the arm configuration. In practice until the end of the last decade, the designer proceeded with the design of each joint mechanism without knowing the actual characteristics of the multi dof motion. Also, the choice of the kinematic scheme and its different parameters, the actuator units, and the control systems was a subject of free speculation, frequently based on experience but lacking any system of method. Hence many parameters, and often the motors were over powered. Hence the need for developing certain criteria and procedures for a systematic choice of manipulator configuration. In the design phase there is no efficient means except simulation to investigate and evalulate the highly non-linear and coupled systems.

The aim of this work is to develop an interactive program for the simulation of all the dynamical values and characteristics of the manipulator operations in a particular taks execution, permitting the designer to view the characteristics in their entirety, and to evaluate a great number of different configurations as fast as possible.

The program consists of four main parts. The first part defines all the vector, matrix and block matrix operations necessary for the simulation algorithm.

The second part is the simulation algorithm. The algorithm automatically forms and solves the mathematical model of the robot dynamics using the block matrix method. The inputs for the algorithm are the manipulator configuration, the initial state and the manipulation task. The output of the algorithm are the drives in the joints, the P-N diagram, the energy consumed for the performance of the task, etc.

The third part is the Editor. It is used to perform interactive editing of the task, state or configuration of the manipulator.

The fourth part, the Command Interpreter, intreprets the commands given by the user, demands the data to be provided, if necessary, then selects the desired primitives

and executes it. For the prevention of the user's careless errors, the program traps them at various places and issues the relevent messages.

The main program is written in Pascal. The subroutines for the drawing of graphs on the graphics terminal is written in Fortran. For Graphic action, PLOT-10 Interactive Graphics Library (IGL) is used.

CHAPTER II

MODELLING

2.1 INTRODUCTION:

The algorithms for modelling Open Chain Active Mechanisms (OCAM) can generally be classified into two groups : analytical and computer oriented. Analytical procedures have appeared before Computer Aided (CA) methods and originate within the multibody satellite dynamics. Unfortunately the application of these methods ' by hand ' is very tedious and are subject to mistakes. Also these algorithms include either unsuitable numerical operations or impose some calculations which are not formalised. For these reasons it becomes necessary to develop CA methods for mathematical modelling. It will enable the designer to analyse a number of different configurations and choose the most appropriate one to the future of the device. The development of CA methods which perform real time calculations of robot dynamics is a direct contribution to the synthesis of control algorithm for practical purposes.

Any CA method must satisfy the following requirements:

a) The input data for the algorithm are : robot configuration, robot state, workspace state, and robot task. Using such input data the computer itself

forms and solves the mathematical model, i.e., robot dynamics. In principle three problems of dynamics may be solved : a direct and an inverse one, or a combination of these two.

b) The algorithm includes no numerical differentiation.

The present CA methods may be divided into three groups:

a) Methods based on the general theorem of dynamics and the Newton-Euler equations,

b) Methods based on the second order Lagrange equations.

c) Methods based on Gibbs-Appel equations and the Gauss principle.

This program uses the general theorem of dynamics and incorporates the Block Matrix method. The Block Matrix method represents the analytically derived mathematical model but by using suitable block formalism the model reduces to the compact matrix form suitable for solving on a computer.

The aim of each CA method is to derive functions f and g such that

$$\ddot{u} = f(u, \dot{u}, P, \text{mechanism configuration})$$

$$P = g(u, \dot{u}, \ddot{u}, \text{mechanism configuration})$$

where u is the generalised coordinate vector and P is the drive vector.

The functions f and g are not some explicitly prescribed or derived function. They represent large computation algorighms. The realisation of the algorithms f and g are specific to and characteristic of each method and it depends on the mechanical approach. The algorithms f and g, although mutually inverse, (f represents the direct problem and g the inverse one) are sometimes realised in rather different ways. Most of the CA methods consider the fifth class kinematic pairs only, i.e., joints permitting only one degree of freedom between the segments. If a compound joint is in question, then it is dissembled into a sequence of fifth class joints with small parameter segments between them.

The following assumptions have been made while forming the mathematical model:

a) All the links are rigid bodies.

b) All the articulations are fifth class pairs.

c) All the articulations are perfect.

d) There are not kinematic singularities.

The overall model is developed in three phases: Geometric, Kinematic, and Dynamic.

2.2 THE GEOMETRIC MODEL:

The kinematic structure of the arm has been modelled based on the Denavit and Hartenberg convention [1].

Referring to the Figure 2.1, the links of the Articulated Mechanical System (AMS) are numbered from zero at the base to N at the End Effector (EE). Links L_{i-1} and L_i are connected at joint T_i. The axis of a joint is defined as the axis of rotation for a revolute joint and as a line parallel to the generatrix for a prismatic joint. A convenient fixed coordinate system is chosen for the AMS. A Body Fixed (BF) coordinate system C_i is attached to each link L_i. The origin of frame C_i is denoted by O_i. The z axis of the frame C_i is oriented along the axis of the joint, T_i and the x axis is directed along the common normal. The y axis is so chosen as to make a right handed coordinate system. The relative position of successive pair axes is described by the use of the unique common perpendicular between by axes of successive coordinate frames. With each link L_i is associated a vector ρ_i defining the centre of mass of L_i with respect to the frame C_i, a mass M_i and an inertia tenser J_i.

Four parameters are used to describe each successive joint and link pair:

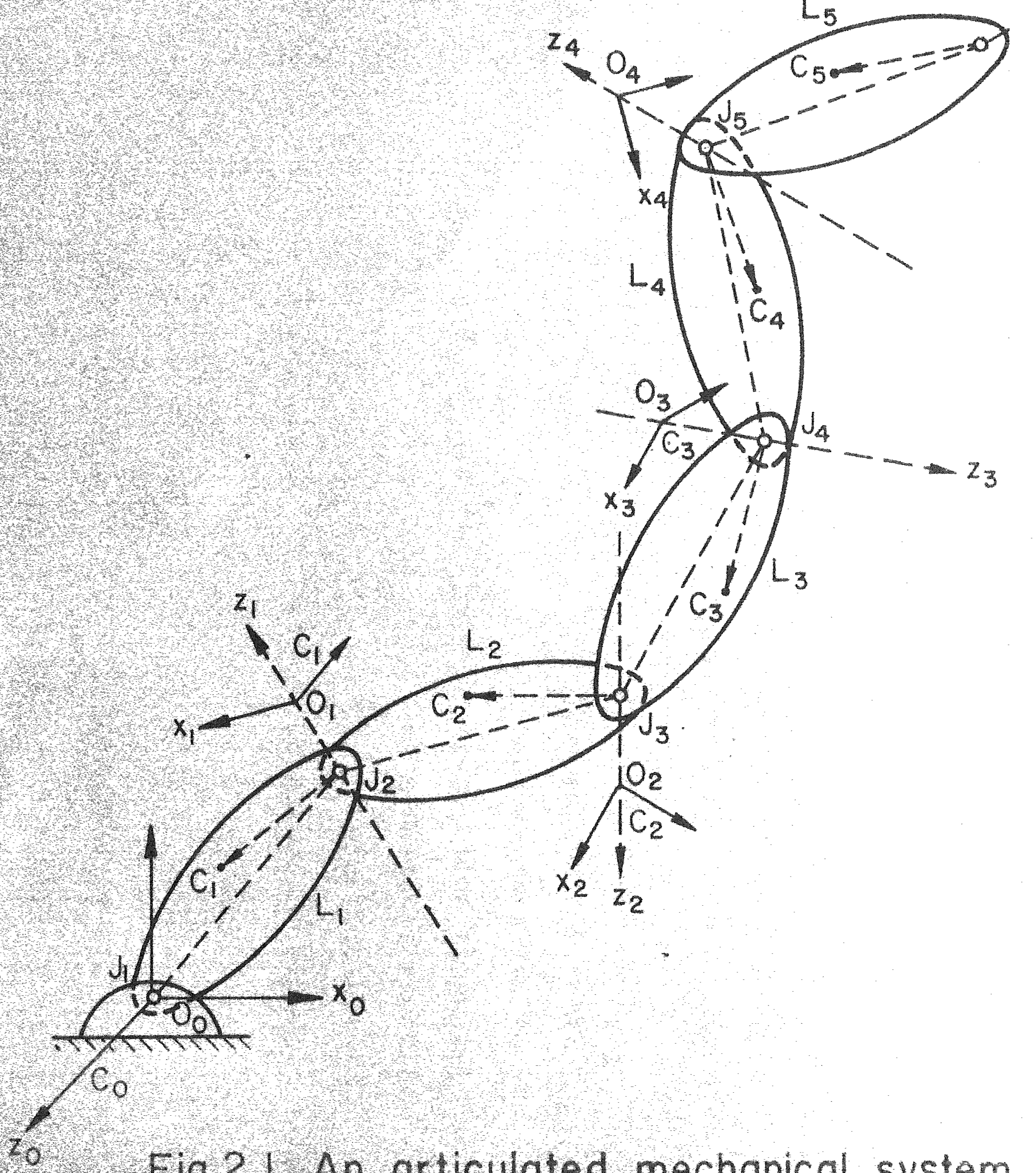


Fig.2.1 An articulated mechanical system

Link length, a - distance between successive z axes

Link twist, α - angle between successive z axes

Joint angle, θ - angle between successive x axes

Joint distance, u - distance between successive x axes.

Refering to Fig. 2.2, the transformation of the frame C_{i-1} into the frame C_i may be represented by the concatenation of the following elementary transformations:

a) $R\ (z_{i-1},\ \theta_i)$ - rotation around z_{i-1} by an angle θ until x_{i-1} becomes parallel to x_i

b) $T\ (z_{i-1}, u_i)$ - translation along z_{i-1} by a distance s until x_{i-1} coincides with x_i

c) $T(x_i,\ a_i)$ - translation along x_i by a distance a until O_{i-1} coincides with O_i

d) $R\ (x_i, \alpha_i)$ - Rotation around x_i by an angle α until C_{i-1} and C_i coincide.

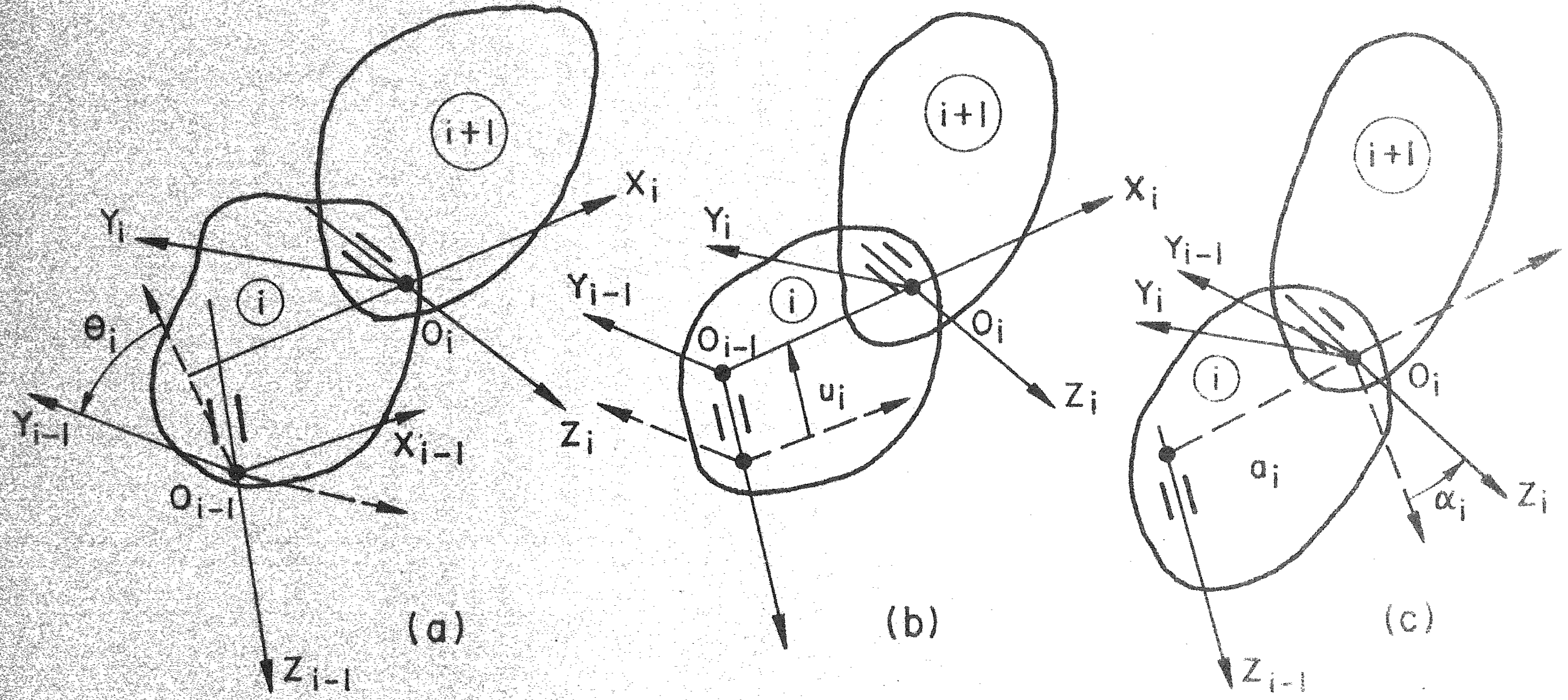


Fig.2.2 Illustrating transition from (i-1)st to ith frame of reference

From these four elementary transformations, a 4 X 4 homogenous transformation matrix $T_{i-1,i}$, which relates the position and orientation of frame C_i to that of frame C_{i-1} may easily be formed.

$$T_{i-1,i} = \begin{bmatrix} \mathrm{Cos}\ \theta_i & \mathrm{Sin}\ \theta_i & 0 & a_i \cdot \mathrm{Cos}\ \theta_i \\ -\mathrm{Sin}\ \theta_i \cdot \mathrm{Cos}\ \alpha_i & \mathrm{Cos}\ \theta_i \cdot \mathrm{Cos}\ \alpha_i & \mathrm{Sin}\ \alpha_i & a_i \cdot \mathrm{Sin}\ \theta_i \\ \mathrm{Sin}\ \theta_i \cdot \mathrm{Sin}\ \alpha_i & -\mathrm{Cos}\ \theta_i \cdot \mathrm{Sin}\ \alpha_i & \mathrm{Cos}\ \alpha_i & u_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ..(2.1)$$

Here, $T_{i-1,i}$ is an orthogonal matrix as it transforms one orthogonal system into another. The transformation between other link coordinate systems may be obtained by the multiplication of intermediate transformation matrices.

It should be noted that for a revolute joint, the joint angle θ_i is the joint variable (the generalieed coordinate), while for a prismatic joint, it is the joint distance u_i. Similarly, the generalised force for a revolute joint is a torque, and for prismatic joint, it is a force.

A point r^p in the frame C_p transforms to the point r^q in the frame C_q according to the equation

$$r^p = T_{p,q} \cdot r^q \quad ..(2.2)$$

Let $A_{i-1,i}$ be a 3 X 3 sub matrix of $T_{i-1,i}$ giving the orientation of the axes of C_{i-1} with reference to C_i

$$A_{i-1,i} = \begin{bmatrix} \cos\theta_i & \sin\theta_i & 0 \\ -\sin\theta_i \cdot \cos\alpha_i & \cos\theta_i \cdot \cos\alpha_i & \sin\alpha_i \\ \sin\theta_i \cdot \sin\alpha_i & -\cos\theta_i \cdot \sin\alpha_i & \cos\alpha_i \end{bmatrix} \qquad \ldots.(2.3)$$

And $l_{i-1,i}$ be 3 X 1 vector giving the position of the origin of the frame C_{i-1} with reference to C_i

$$l_{i-1,i} = [\; a_i \cdot \cos\theta_i \quad a_i \cdot \sin\theta_i \quad u_i \;] \qquad \ldots.(2.4)$$

The equation 2.2 may also be written as

$$r^{i-1} = A_{i-1,i} \; r^i + l_{i-1,i} \qquad \ldots.(2.5)$$

Then for a vector V_i,

$$V_i^p = A_{p,q} \; V_i^q \qquad \ldots.(2.6)$$

where $A_{p,q}$ is obtained by the multiplication of intermediate transformation matrices

$$A_{p,q} = A_{p,p+1} \cdot A_{p+1,p+2} \; \ldots.. A_{q-1,q}$$

$A_{o,i}$ is written simply as A_i and $l_{o,i}$ as l_i

Applying equations 2.5 and 2.6 repeatedly, we get

$$r_i = \sum_{j=0}^{i} A_j \, l_{j,j} + A_i \, r_i^i \qquad \ldots.(2.7)$$

$$V_i = A_i \, V_i^i \qquad \ldots.(2.8)$$

The three columns of the matrix A_N represents the orientation of the axes of the frame C_N in terms of the generalised coordinates, and the vector l_N represents the position vector of the centre of gravity of the EE in the external coordinate system. Thus the geometric model enables us to convert internal coordinates to external cordinates.

2.3 KINEMATIC MODEL:

The derivation of the equations constituting the kinematic and dynamic model is very lengthy and complex, and is discussed in [6]. The analytical equations themselves are very long . However, by using block matrix formalism, the equations are reduced to a very compact form. The equations, are presented here only in their final form [7].

Let $a_i, \ldots a_N$ be a set of vectors, and let us define the Block vectors a and a^o of dimension (NX1 (3X1))

$$a = [\, a_1^1 \,, \ldots \, a_N^N \,]^T$$

$$a^o = [\, a_1 \; \ldots . \; a_N]^T$$

Let E_3 be a 3 X 3 unit matrix, and E_N, a N X N unit matrix let V be the (N X N (3 X 3)) block matrix.

$$V = \begin{bmatrix} E_3 & 0 & \cdots\cdots & 0 \\ E_3 & E_3 & \cdots\cdots & 0 \\ \cdot & & & \\ \cdot & & & \\ E_3 & E_3 & \cdots\cdots & E_3 \end{bmatrix}$$

Further, let us define the link type matrix, S (N X N), and the block matrix ν (N X N (3 X 1))as follows

$$S = \text{diag}\ [\ s_1 \quad s_2 \quad \cdots\cdots \quad s_N\ ] \qquad ..(2.9)$$
$$\nu = \text{diag}\ [\ \nu_1 \quad \nu_2 \quad \cdots\cdots \quad \nu_N\ ]$$

where $\nu_i = [\ 0 \quad \text{Sin}\ \alpha_i \quad \text{Cos}\ \alpha_i\ ]^T$

and s_i is an indicator, whose value is 0 if the ith joint is revolute and 1 if it is prismatic.

Let A be the orientation block matrix (N X N 3 X 3))

$$A = \begin{bmatrix} E_3 & 0 & 0 \cdots\cdots & 0 \\ A_{21} & E_3 & 0 \cdots\cdots & 0 \\ A_{31} & A_{32} & E_3 \cdots\cdots & 0 \\ \cdot & & & \\ \cdot & & & \\ A_{N1} & A_{N2} & A_{N3} \cdots\cdots & E_3 \end{bmatrix}$$

Now, let us define two functions λ and Λ as follows:

$$\lambda(V_i) = \begin{bmatrix} 0 & -V_{iz} & V_{iy} \\ V_{iz} & 0 & -V_{ix} \\ -V_{iy} & V_{ix} & 0 \end{bmatrix} \qquad ...(2.10)$$

where $V_i = [\ V_{ix}\ V_{iy}\ V_{iz}]^T$

$\Lambda(V) = \text{diag} \; [\; \lambda(V_i) \quad \lambda(V_2) \; \ldots\ldots \; \lambda(V_N)]$

where V_i is a vector (3X 1)

Let $q = [\; q_1 \; q_2 \; \ldots q_N \;]^T$ be the vector of internal coordinates (N X 1) and $X = [X_1 \; X_2 \; \ldots\ldots \; X_N \;]^T$, the vector of external coordinates (N X 1) . If v is the linear velocity vector, and ω , the angular velocity vector, then $X = [v \; \omega]^T$ is a (2 X 1,(3 X 1)) velocity block matrix.

Now, we have the following rèlations for velocity block matrix

$$\dot{X} = B\dot{q} \qquad \ldots.(2.12)$$

where B is a (2 X 1(N XN (3 X 1))) block matrix

$$B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}$$

$$\begin{aligned} B_1 &= -\; (A\Lambda\,(1) + \Lambda\,(\rho) \quad A\,\nu\,(E-S) + A\,\nu\,s \\ B_2 &= \quad A\;\nu(\;E-S\;) \end{aligned} \qquad \ldots(2.13)$$

For velocities expressed in the external coordinate system, we have

$$\dot{X}^o = \; B^o \; \dot{q} \qquad \ldots\; (2.14)$$

where

$$B^o = \begin{bmatrix} B_1^o \\ B_2^o \end{bmatrix} \qquad \ldots\; (2.15)$$

$$B_1^o = -\,\Lambda^*\;(\,\rho\,)\;e^o\;(E-S)\;\dot{q} + \; VSe^o\dot{q}$$

$$B_2^o = \quad V\;e^o\;(E-S)\quad \dot{q}$$

$$e^o = \text{diag}\;[e_1 \ldots e_N]$$

$$\Lambda^{*}(\rho) = \begin{bmatrix} \lambda(\rho_{o1}) & 0 & \cdots & 0 \\ \lambda(\rho_{o2}) & \lambda(\rho_{12}) & \cdots & 0 \\ \vdots & & & \\ \lambda(\rho_{oN}) & \lambda(\rho_{1N}) & \cdots & \lambda(\rho_{N-1,N}) \end{bmatrix}$$

Now, let w and ϵ be linear and angular acceleration vectors (3 X 1) respectively. Then $\ddot{X} = [\, w \ \varepsilon]^T$

We have the following relation for acceleration block vector

$$\ddot{X} = B\ddot{q} + D\dot{q} \qquad \ldots(2.16)$$

where

$$D = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}$$

$$D_1 = (\, A\Lambda(1) + \Lambda(\rho)\,)\ A\Lambda(\omega)\ \nu(E-S - (A\Lambda(\omega)\Lambda(1) + \Lambda(\omega)\,\Lambda(\rho))\ A\nu(\,E-S\,) + 2A\Lambda(\omega)\ \nu S \ \ldots$$

$$D_2 = A\ (\Lambda(\omega)\ \ \nu(E-S) \qquad \ldots(2.17)$$

In the external coordinate system,

$$\ddot{X}^o = B^o\ddot{q} + D^o\dot{q} \qquad \ldots(2.18)$$

where

$$D^o = \begin{bmatrix} D_i^o \\ D_2^o \end{bmatrix}$$

$D_1^o = [D_1^1 \ \ldots.\ D_N^1\,]^T$ dimension (N X N (3 X 1))

$D_i^1 = Q\ (\ D_{i1}^1 + D_{i2}^1)$ dimension (3 X N)

$$D_{i1}^{1} = \begin{bmatrix} d_{11}^{1} & \cdots\cdots & d_{1i}^{1} & 0 & \cdots\cdots & 0 \\ \cdot & & & & & \\ \cdot & & & & & \\ d_{i-1,i}^{1} & & d_{i,1,i}^{1} & 0 & \cdots\cdots & 0 \\ 0 & \cdots\cdots & & 0 & \cdots\cdots & 0 \\ \cdot & & & & & \\ 0 & \cdots\cdots & & 0 & \cdots\cdots & 0 \end{bmatrix} \qquad \ldots(2.19)$$

$$d_{kj}^{1} = \lambda(e_{j-1})\,\lambda(e_k)\,\rho_{j-1,i}\,(1-s_k)\,(1-s_j)$$

$$\begin{bmatrix} 0 & \cdots\cdots & d_{12}^{2} \cdots\cdots & d_{1i}^{2} & \cdots\cdots & 0 & \cdots\cdots & 0 \\ d_{21}^{2} & & 0 \cdots\cdots & d_{2i}^{2} & & 0 & \cdots\cdots & 0 \\ \cdot & & & & & & & \\ \cdot & & & & & & & \\ d_{i1}^{2} & & d_{i2}^{2} \cdots\cdots & 0 & & 0 & \cdots\cdots & 0 \\ \cdot & & & & & & & \\ 0 & & 0 & 0 & & 0 & \cdots\cdots & 0 \end{bmatrix}$$

$$d_{kj}^{2} = \lambda(e_{k-1})\,e_{j-1}\,(1-s_k)\,s_j$$

$$d_{jk}^{2} = d_{kj}^{2}$$

$$D_2^{o} = [D_1^2 \quad \cdots\cdots \quad D_N^2]^T \qquad \text{dimension } (N \times N\,(3 \times 1))$$

$$D_i^2 = \dot{Q}\;H_i^2$$

$$\dot{Q} = [\,\dot{q}_1 E_3 \quad \dot{q}_2 E_3 \quad \cdots\cdots \quad \dot{q}_N E_3\,]$$

$$H_i^2 = \begin{bmatrix} 0 & 0 & \cdots & 0 & \cdots & 0 \\ \sigma_1\sigma_2\lambda(e_o)e_1 & 0 & \cdots & 0 & \cdots & 0 \\ \sigma_1\sigma_3\lambda(e_o)e_2 & \sigma_2\sigma_3\lambda(e_1)e_2 & & 0 & & 0 \\ \sigma_1\sigma_i\lambda(e_o)\ e_{i-1} & \sigma_2\sigma_i\lambda(e_1)e_{i-1} & \cdots & \sigma_{i-1}\sigma_i\lambda(e_{i-2})e_{i-1} & \cdots & 0 \\ 0 & & & & & \\ \vdots & & & & & \\ 0 & 0 & \cdots & 0 & \cdots & 0 \end{bmatrix}$$

$\sigma_i = 1-s_i$

We now have the expressions for the velocity and acceleration of the links in the external coordinate system as well as the BF system. These expressions constitute the kinematic model.

2.4 DYNAMIC MODEL:

The dynamic equations are derived on the basis of D ' Alambert's principle by interrupting the chain fictitiously at a joint and balancing the forces and moments. In this way, N scalar equations are obtained, and transformed into matrix form using block formalism.

Let us introduce the following block matrices of dimension (NXN (3X3)).

$$m = \text{diag} \; [\, m_1E_3 \;\; \ldots\ldots m_NE_3 \,]$$

$$J^o = \text{diag} \; [\, J_1^o \;\; \ldots\ldots J_N^o \,]$$

$$A_o = \text{diag} \; [[\, A_{1o} \;\; \ldots\ldots A_{No} \,]$$

The expressions for the block vectors of the resultant inertial forces and moments can be written together as

$$\begin{bmatrix} F_I^o \\ M_I^o \end{bmatrix} = -\mathcal{J} B^o q - C^o q \qquad \ldots.(2.20)$$

where

$$\mathcal{J} = \begin{bmatrix} m & 0 \\ 0 & J^o \end{bmatrix}$$

$$C^o = \begin{bmatrix} m\, D_1^o \\ \Omega^o J^o \overset{o}{B_2} + J^o D_2^o \end{bmatrix}$$

$$\Omega = \Lambda\,(\omega^o) \qquad \ldots.\ (2.21)$$

Let us further introduce the vector of the drives P of dimension (NX1)

$$B = [\, P_i \;\ldots.. \; P_N]^T$$

Then the dynamic equations can be written as

$$W\ddot{q} = B'\dot{q} + C'\, M_E^o + D'\, (G^o + F_E^o\,) + P \qquad \ldots\ (2.22)$$

where

$$W = B^{o^T} \mathcal{J} B^o$$
$$B' = B^{o^T} \quad C^o$$
$$C' = B_2{}^{o^T}$$
$$D' = B_1{}^{o^T} \qquad \ldots(2.23)$$

by introducing

$$U(q,\dot{q}) = B' \dot{q} + C' M_E^o + D' (G^o + F_E^o) \quad \ldots.(2.24)$$

the equation acquires the from

$$W(q)\ddot{q} = U(q,\dot{q}) + P \qquad \ldots(2.25)$$

Thus we have described the dynamics of the AMS by means of N differential equations in matrix form.

CHAPTER III

SIMULATION

3.1 INTRODUCTION:

The notion of the simulation of dynamics usually involves the solution of the inverse problem of dynamics, i.e. the determination of the motion for prescribed generalised forces. In this case, the simulation is considered somewhat more liberally so that it also includes the notion of the simulation of the direct problem.

The Fig. 3.1 shows the different models and the different levels of control of a typical manipulator organised in a hierarchial fashion. The highest level defines the task to be carried out, the strategic level divides the imposed task into elementary functions, the tactical level performs the distribution of an elementary movement to the motion of each degree of freedom of the robot, and the executive level executes the imposed motion of each dof. The model developed in the previous chapter is used as the basis for the development of the algorithm for the simulation of the manipulator dynamics, and thus the synthesis of the tactical level.

Before proceeding further, it will be useful to note an important point. The task of a manipulator may

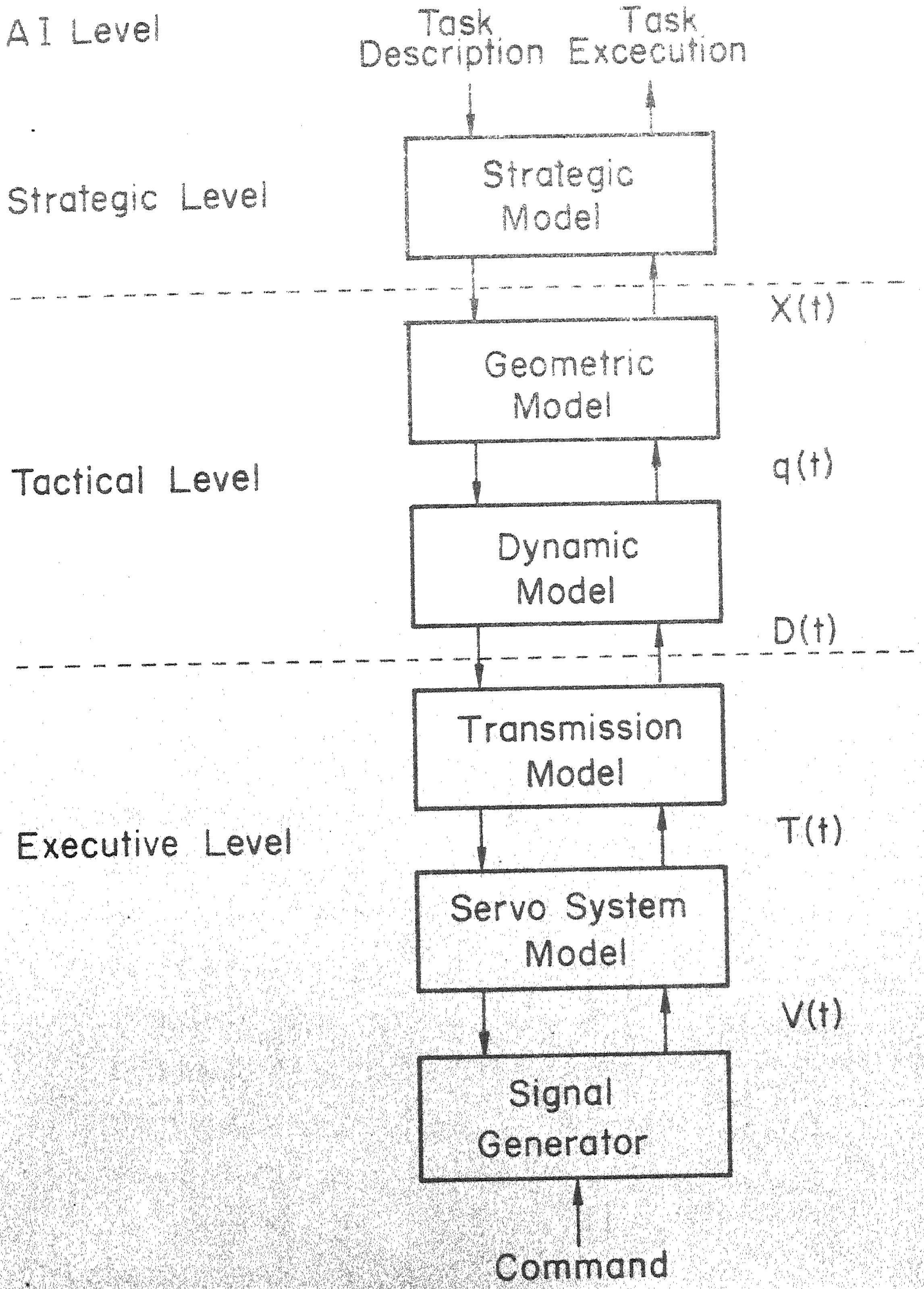


Fig. 3.1 The Different Control Levels And Model of a Typical Manipulator.

be defined as the process of transferring the system state from one bounded region of initial states into another bounded region in the state space within a finite settling time, the system state being in the bounded region of the state space during the transfer. The state of the Articulated Mechanical System (AMS) , at any instant may be described by means of a vector of coordinates. The coordinates are called internal coordinates if the elements of the vector represent the position of the articulation at that time instant. If they represent the coordinates of a predefined point on the End Effector (EE) with reference to the external coordinate system, then they are called the external coordinates . However, in practice, the task is prescribed neither by means of internal coordinates, nor the external coordinates, but by the s· called functional coordinates, as it is necessary to consider the functional robot motion. This is a motion satisfying certain practical demands. For instance, for a particular operation, the task of positioning the minimal configuration may be given in terms of spherical coordinates, and the task of orientation of the the EE may be given in terms of three Eular angles. For another operation it may be more convenient to give the orientation of the EE in terms of a direction and an angle of rotation round it.

Transformation of the functional coordinates into external coordinates is fairly simple, but the transformation of the external coordinates to internal coordinates is extremely complicated not only because the transformation is not explicit, but because it cannot even be numerically approximated due to the complexity of the system. Also, a set of external coordinates may not have a unique set of corresponding internal coordinates. The external coordinates define the position and orientation of the EE , which we may call 'pose' of the manipulator. On the other hand the internal coordinates determine the 'posture' of the manipulator, i.e., the geometrical configuration adopted by the manipulator while holding an object in a particular pose. The posture of a manipulator completely defines it pose, but for a particular pose a manipulator may be in different postures. A 3 dof manipulator has only one posture in general, and a 6 dof one is believed to have 32 postures in general. A human arm can adopt an infinite number of postures.

3.2 THE SIMULATION ALGORITHM:

Let us designate by η a function which transforms the internal coordinates into external coordinates.

$$X = \eta\ (q) \qquad \text{........} \ (3.1)$$

Now, for the operation of the Computer Aided (CA) method of forming the mathematical model, it is necessary to know q, $\dot{q}$ and q at each time instant. However, only q appears as input since q and $\dot{q}$ are calculated by integration starting with known initial state q^o and $\dot{q}^o$. So in order to realise the simulation, it is necessary to develop a procedure for calculating q from the known state q, $\dot{q}$, and known external coordinate vector, X.

By differentiating equation 3.1 twice,

$$\dot{X} = \frac{d\eta}{dq} \cdot \dot{q} \qquad \ldots (3.2)$$

$$X = \frac{d\eta}{dq} \cdot \dot{q} + \frac{d^2\eta}{dq^2} \cdot \dot{q}^2 \qquad \ldots (3.3)$$

Let $B = \frac{d\eta}{dq}$, $A = \frac{d^2\eta}{dq^2} \cdot \dot{q}^2$ Then

$$\ddot{X} = B \ddot{q} + A \qquad \ldots (3.4)$$

B is called the Jacobian matrix (order NXN). B and A are functions of the state q, $\dot{q}$, and are calculated numerically by means of the kinematic model developed in the previous chapter. Then q is calculated by the relation

$$\ddot{q} = B^{-1} (\ddot{X} - A) \qquad \ldots (3.5)$$

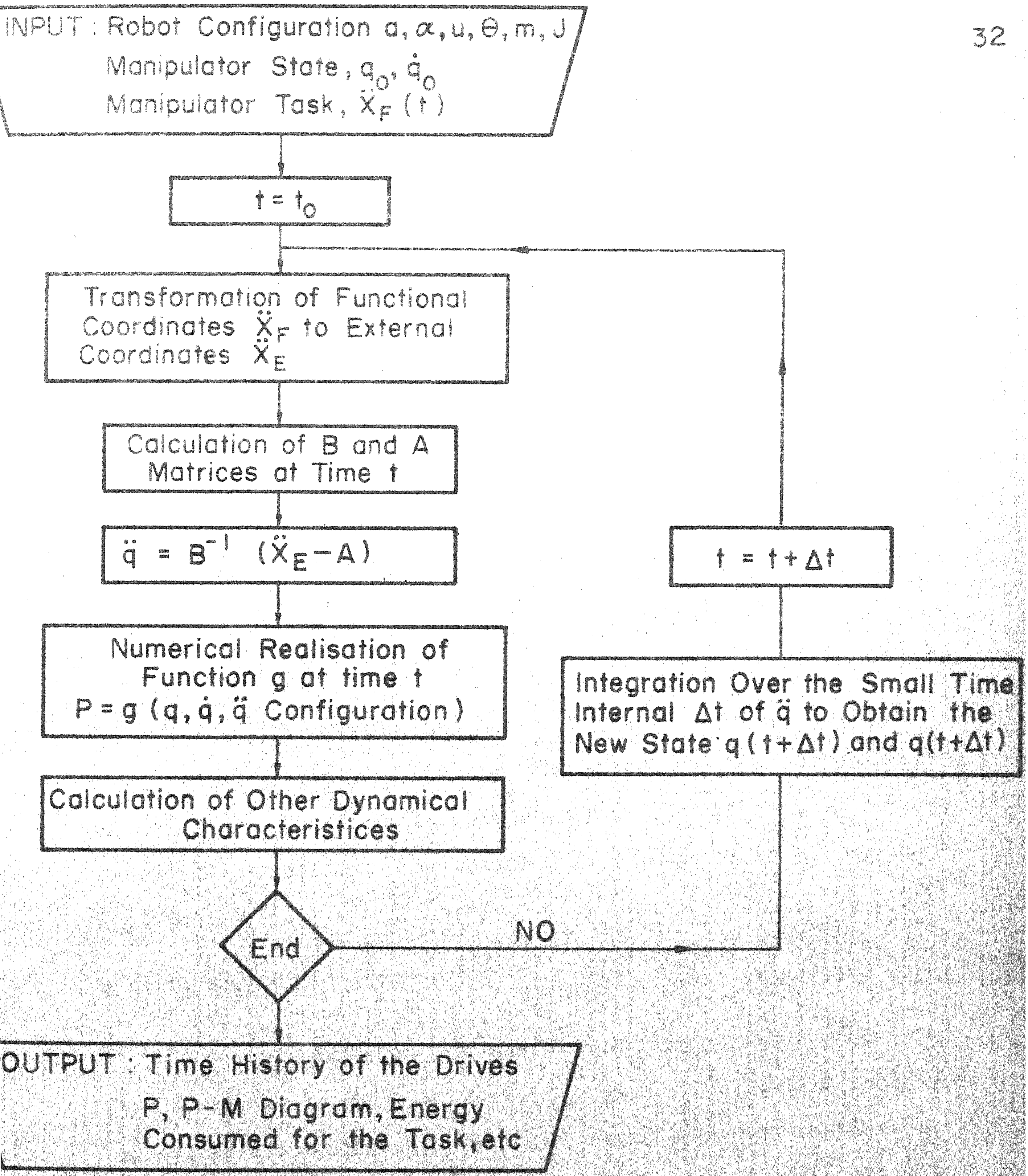


FIG. 3.2 FLOW CHART OF THE SIMULATION ALGORITM .

$\ddot{X}$ can be represented by

$$\ddot{X} = \begin{bmatrix} w \\ \varepsilon \end{bmatrix}$$

where w is the linear acceleration, and ε is the angular acceleration of the centre of gravity of the EE.

From Eqn. 2.16 , we can obtain

$$\begin{aligned} \ddot{X} &= B\ddot{q} + D\dot{q} \\ &= B\ddot{q} + A \qquad \ldots(3.6) \end{aligned}$$

Now from Eqn. 2.25 we can calculate the drives

$$\begin{aligned} P &= g\ (q, \dot{q}, q\ , \text{configuration}) \\ &= W\ddot{q} - U \qquad \ldots\ (3.7) \end{aligned}$$

By integrating $\ddot{q}$, we get the state **q**, $\dot{q}$ at the next time instant. With the new state and the corresponding value of the functional coordinates acceleration , X_F we can repeat the process. The simulation algorithm is presented in Fig. 3.2.

3.3 ADJUSTMENT BLOCKS :

As pointed out earlier, although the manipulation task can be defined fully by means of external coordinates, they are unsuitable for setting. For the various individual classes of tasks, the most suitable variables are given as inputs, which naturally reflect the type of the

task. These are called the, functional coordinates. The transformation of the functional coordinates to the external coordinates is done in a block, known as the adjustment block, within the simulation algorithm.

Before proceeding with the various classes of tasks, let us define some notions precisely. By positioning we mean moving the centre of gravity of the last segment (or some predefined point on it) to some desired point in the work space according to a prescribed motion law.

Full orientation of the body in space means an exactly determined angular position of the body with respect to the external space.

Partial orientation of the body means that the given body axis coincides with a prescribed direction is space.

To solve the positioning task, which is part of every manipulation task, three dof are necessary.

To solve the positioning task along with the task of partial orientation, five dof are necessary.

To solve the positioning task along with the task of full orientation, six dof are needed.

Now some typical classes of tasks and ways of using the dof will be analysed.

A) A manipulator with four dof solves the positioning task by using three dof, and with the one remaining performs operations frequently sufficient for many practical tasks.

1. The task is that of positioning in the cartesian coordinate system, i.e. $x(t)$, $y(t)$, $z(t)$ for the centre of gravity of the EE, and the fourth dof is prescribed directly ($q_4(t)$).

2. Same as 1., but positioning is given in cylindrical coordinates (t), $\theta(t)$, $z(t)$.

3. Same as 1., but positioning is given in spherical coordinates $r(t)$, $\theta(t)$, $\phi(t)$.

B) A manipulator with five dof solves the positioning and partial orientation task.

1. The task is given in the form of positioning (A1 , A2 or A3) and partial orientation.

C) A manipulator with six dof solves the positioning and full orientation task, as well as all the problems in which fewer dof are needed (when compensation of the dof surplus is done).

1. The task is given in the form of positioning (A1,A2, or A3), and full orientation of the EE in terms of the three Euler angles, $\Theta(t)$, $\psi(t)$, $\beta(t)$.

2. The task is given in the form of positioning (A1,A2, or A3) and full orientation is given in terms of one direction $\Theta(t)$ and $\beta(t)$, and an angle of rotation around it, ψ (t).

3. The task is given in terms of positioning as in 2 plus partial orientation. Motion along one dof is prescribed directly ($q_k(t)$).

The derivation of the adjustment blocks for these classes of task will now be given briefly. We will use the same of matrix notation for X_E (external coordinates)i.e.

$$\ddot{X}_E = \begin{bmatrix} w \\ \varepsilon \end{bmatrix} = B\ddot{q} + A$$

Let $B = \begin{bmatrix} \Omega \\ \Gamma \end{bmatrix}$ and $A = \begin{bmatrix} \Theta \\ \phi \end{bmatrix}$

A1 The input to the block is X_F (functional coordinates)

$$\ddot{X}_F = [\ \ddot{x}\ \ \ddot{y}\ \ \ddot{z}\ \ \ddot{q}_4\ ]^T \qquad \text{...(3.7)}$$

Hence, $w = [\ \ddot{x}\ \ \ddot{y}\ \ \ddot{z}\ \ ]^T$

Using the equation 3.5 $\ddot{q}_1, \ddot{q}_2$ and $\ddot{q}_3$ are calculated $\ddot{q}_4$ is prescribed directly.

<u>A2</u> $\ddot{X}_F = [\ddot{\rho}\ \ddot{\theta}\ \ddot{z}\ \ddot{q}_4]^T$

The following equations can easily be derived using elementary transformation.

$$\begin{aligned} w_x &= w_\rho \cos\theta - w_\theta \sin\theta \\ w_y &= w_\rho \sin\theta + w_\theta \cos\theta \\ w_z &= \ddot{z} \end{aligned} \qquad \ldots (3.8)$$

where $w_\rho = \ddot{\rho} - \rho\dot{\theta}^2$, $w_\theta = \rho\ddot{\theta} + 2\dot{\rho}\dot{\theta}$, $w_z = \ddot{z}$

ρ, $\dot{\rho}$. θ, $\dot{\theta}$ etc are obtained by integration of $\ddot{\rho}$, $\ddot{\theta}$ etc. the rest is as in A1.

<u>A3</u> $\ddot{X}_F = [\ddot{r}, \ddot{\theta}, \ddot{\beta}, \ddot{q}_4]^T$.

Again, the following equations can easily be derived. Please refer to Fig. 3.3. a,b,c.

$$\begin{aligned} w_x &= w_r \cos\ \cos\theta - w_\theta \sin\theta - w_\beta \sin\ \cos\theta \\ w_y &= w_r \cos\ \sin\theta + w_\theta \cos\theta - w_\beta \sin\ \sin\theta \\ w_z &= w_r \sin + w_\beta \cos \end{aligned} \qquad \ldots (3.9)$$

where

$$\begin{aligned} w_r &= \ddot{r} - r\dot{\beta}^2 - r\cos^2\beta\ \dot{\theta}^2 \\ w_\theta &= 2\dot{r}\dot{\theta}\cos\beta + r\ddot{\theta}\cos\beta - 2r\dot{\beta}\dot{\theta}\sin\beta \\ w_\beta &= 2\dot{r}\dot{\beta} + r\ddot{\beta} + r\sin\beta\cos\beta\ \dot{\theta}^2 \end{aligned}$$

<u>C1</u> If positioning is prescribed in cartesian coordinates,

$\ddot{X}_F = [\ddot{x}\ \ddot{y}\ \ddot{z}\ \ddot{\theta}\ \ddot{\Psi}\ \ddot{\beta}]^T$.

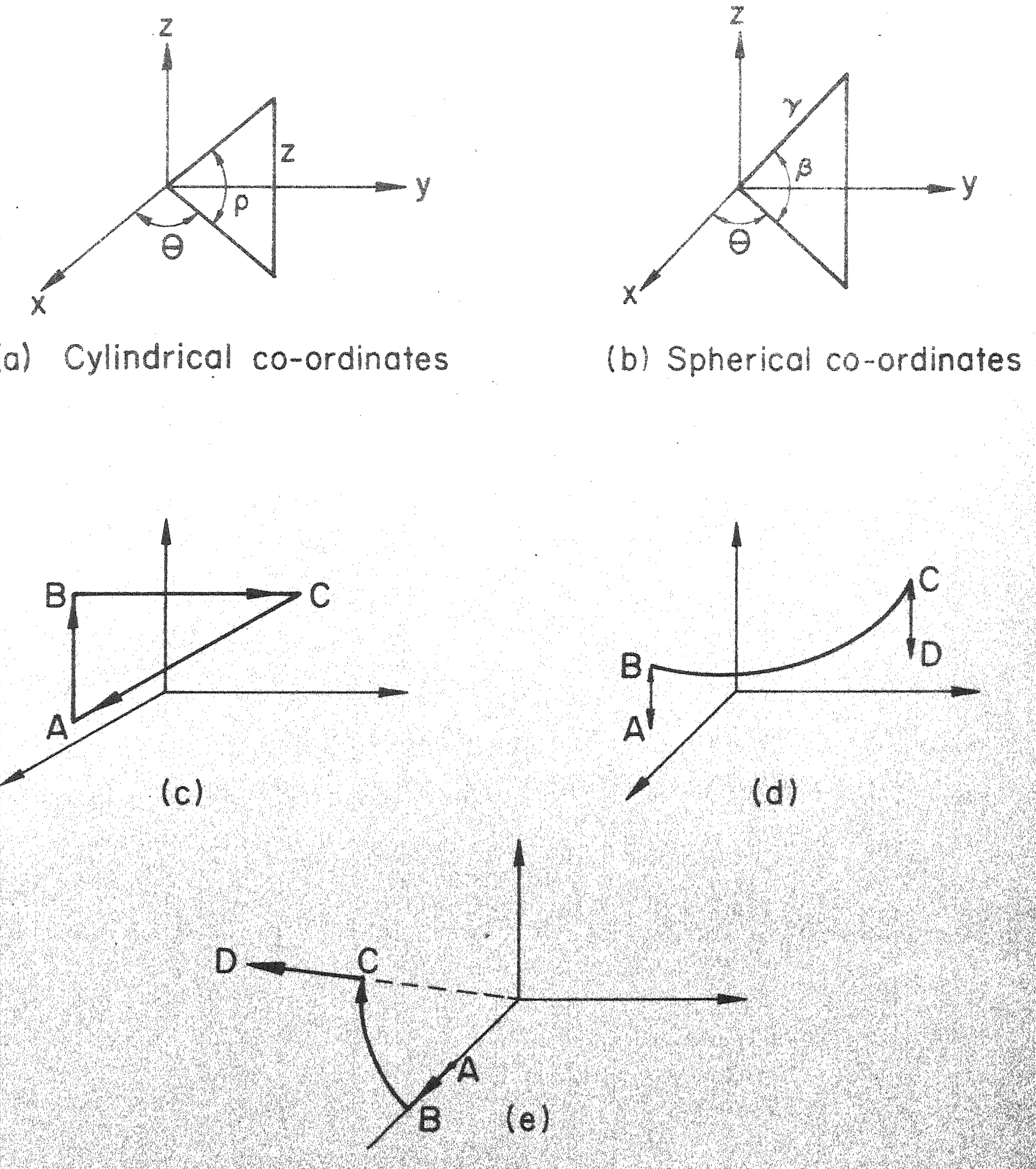


Fig.3.3 Various trajectories of the manipulator tip

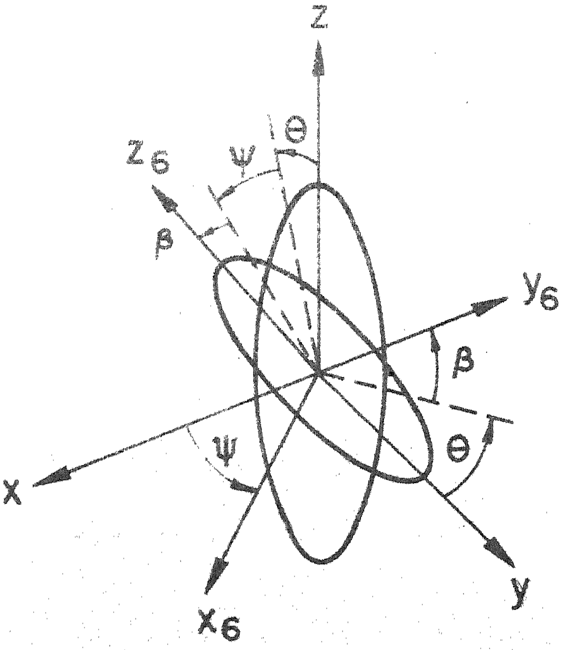


Fig.3.4 Euler angles of the BF system (x_6, y_6, z_6) relative to the external system (x, y, z)

The positioning may also be prescribed in cylindrical or spherical coordinates. In any case, w is calculated as in A1,A2,or A3, as required. Please refer to Fig. 3.4.

The angular acceleration is given by

$$\varepsilon = A_6 \left(\pi \begin{bmatrix} \ddot{\Theta} \\ \ddot{\psi} \\ \ddot{\beta} \end{bmatrix} + 1_{\pi} \begin{bmatrix} \dot{\psi} & \dot{\beta} \\ \dot{\beta} \, , & \dot{\Theta} \\ \dot{\Theta} \, ' & \dot{\psi} \end{bmatrix} \right)$$

where

$$\pi = \begin{bmatrix} \mathrm{Cos}\ \psi & 0 & 1 \\ \mathrm{Sin}\ \psi \cdot \mathrm{Sin}\,\beta & \mathrm{Cos}\,\beta & 0 \\ \mathrm{Sin}\ \psi \cdot \mathrm{Cos}\,\beta & -\mathrm{Sin}\,\beta & 0 \end{bmatrix}$$

$$1_{\pi} = \begin{bmatrix} 0 & 0 & -\mathrm{Sin}\ \psi \\ -\mathrm{Sin}\ \beta & \mathrm{Sin}\ \psi \cdot \mathrm{Cos}\,\beta & \mathrm{Cos}\ \psi \cdot \mathrm{Sin}\ \psi \\ -\mathrm{Cos}\,\beta & -\mathrm{Sin}\,\psi \cdot \mathrm{Sin}\,\beta & \mathrm{Cos}\ \psi \cdot \mathrm{Cos}\ \beta \end{bmatrix} \qquad \ldots(3.10)$$

A_6 is the transition matrix of the last segment

$$A_6 = A_1\ A_2 \ \ldots\ldots\ A_6.$$

C2 This method is suitable in many practical cases, for eg. spraying powder along a prescribed path, or screwing in a bolt.

$$\ddot{X}_F = [\ \ddot{x}\ \ \ddot{y}\ \ \ddot{z}\ \ \ddot{\Theta}\ \ \ \ddot{\beta}\ \ \ \ddot{\psi}]^T$$

w is determined as in C1

Refering to Fig. 3.5, the direction of any line may be prescribed by means of two angles θ and β. Rotation around this line is given by ψ.

ε is calculated from the relation

$$\lambda(\varepsilon) = \ddot{A} A^{-1} - [\lambda(\omega)]^2 \qquad \ldots (3.11)$$

where

$$A = A_1 A_2 A_3$$

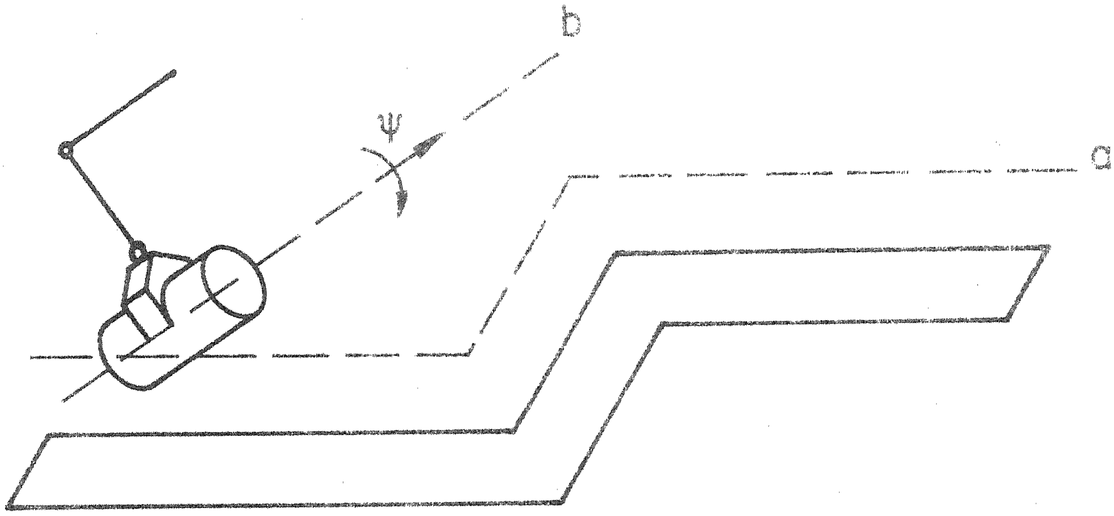
$$A_1 = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix}$$

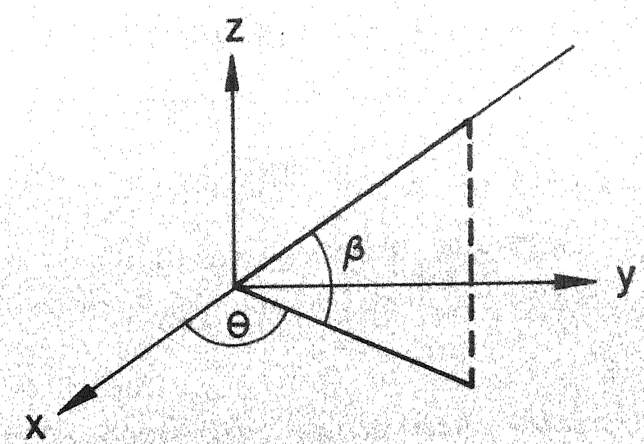
$$A_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix}$$

$$\dot{A} = \dot{A}_1 A_2 A_3 + A_1 \dot{A}_2 A_3 + A_1 A_2 \dot{A}_3$$

$$\begin{aligned} \ddot{A} = {} & \ddot{A}_1 A_2 A_3 + \dot{A}_1 \dot{A}_2 A_3 + \dot{A}_1 A_2 \dot{A}_3 + \qquad \ldots (3 \\ & \dot{A}_1 \dot{A}_2 A_3 + A_1 \ddot{A}_2 A_3 + A_1 \dot{A}_2 \dot{A}_3 + \\ & \dot{A}_1 A_2 \dot{A}_3 + A_1 \dot{A}_2 \dot{A}_3 + A_1 A_2 \ddot{A}_3 \end{aligned}$$



(a) Spraying powder along a prescribed trajectory



(b) External angles θ, β

Fig. 3.5

B1 In this case, the manipulator has five dof, for which positioning is prescribed as in A1, A2 or A3 and the orientation is prescribed by the requirement that the EE should coincide with a given direction in space

$$\ddot{X}_F = [\ \ddot{x}\ \ \ddot{y}\ \ \ddot{z}\ \ \ddot{\theta}\ \ \ \beta]$$

where the angles θ and specify the direction, as in C2. w is calculated as in C2. ϵ is claculated as follows.

$$\varepsilon = \begin{bmatrix} \ddot{h}_1 \\ \ddot{h}_2 \end{bmatrix}$$

where

$$\begin{aligned} \ddot{h}_1 &= -\operatorname{Cos}\beta\ \dot{\beta}^2\ \operatorname{Cos}\theta - \operatorname{Sin}\beta\ \ddot{\beta}\operatorname{Cos}\theta + \\ &\quad 2\operatorname{Sin}\beta\ \dot{\beta}\ \operatorname{Sin}\theta\ \dot{\theta} - \operatorname{Cos}\beta\ \operatorname{Cos}\theta\ \dot{\theta}^2 \\ &\quad - \operatorname{Cos}\beta\ \operatorname{Sin}\theta\ \ddot{\theta} \\ \ddot{h}_2 &= -\operatorname{Cos}\beta\ \dot{\beta}^2\ \operatorname{Sin}\theta - \operatorname{Sin}\beta\ddot{\beta}\operatorname{Sin}\theta - \\ &\quad - 2\operatorname{Sin}\beta\dot{\beta}\operatorname{Cos}\theta\ \dot{\theta} - \operatorname{Cos}\beta\ \operatorname{Sin}\theta\ \dot{\theta}^2 \\ &\quad + \operatorname{Cos}\beta\operatorname{Cos}\theta\ \ddot{\theta}\ . \end{aligned} \qquad \ldots.(3.13)$$

C3 In this case five functional coordinates are prescribed exactly as in B1 and the remaining dof is prescribed directly namely q_k (t)

$$\ddot{X}_F = [\ddot{x}\ \ \ddot{y}\ \ \ddot{z}\ \ \ddot{\theta}\ \ \ddot{\beta}\ \ \ddot{q}_6]$$

The adjustment block is derived as in B1.

3.4 OTHER DYNAMICAL CHARACTERISTICS :

(a) P-N Diagram:

Since the drives and generalised velocities, q, are calculated at each step of the simulation, it is possible to draw a diagram for each joint, the characteristics of the driving motor torque P versus the motor rpm N, i.e. the diagram P-N for each motor. Such a diagram is very useful during the synthesis and choice of the servosystems. The producer gives the P_{max} - N motor characteristics in the catalogue where P_{max} is the maximal motor torque at motor rpm N. By comparing the necessary characteristics obtained by means of simulation with the one from the catalogue, one can decide whether the chosen motor suits its applications.

The diagram P-N is obtained in such a way that for each time instant and for joint k ,

$$N = R\dot{q}_k$$

$$P = \eta(R)\ P_k / N \qquad \ldots\ldots (3.14)$$

where R is the reduction ratio of the subject joint and η (R) is its mechanical efficiency. Repeating the procedure for each time instant, the desired diagram is obtained.

(b) Energy Consumed:

During the simulation, energy consumed during each step Δt_i is found, and the total energy is calculated by summation of these values.

$$E^{i} = E^{i-1} + E_{\Delta t_i} \qquad \text{....(3.15)}$$

where E^i is the total energy consumed including during the ith time step, and $E_{\Delta t_i}$ is the energy consumed during the ith time interval. To calculate $E_{\Delta t_i}$ the everage drive value on the interval is taken

$$P^{i}_{med} = \frac{1}{2}\left(P^{i-1} + P^{i}\right) \qquad \text{....(3.16)}$$

Now,

$$E_{\Delta t_i} = \Delta q^{i^T} . P^{i}_{med} \qquad \text{....(3.17)}$$

where $\Delta q^i = q^i - q^{i-1}$. The elements of the vectors q^i and P^i_{med} are absolute value. The average drive value is used to avoid more complex interpolation.

We can thus obtain the total energy consumed for the given manipulation task.

Thus, we now have a simulation algorithm which has the following inputs: the manipulator configuration, the manipulator state, and the manipulation task in the form most suited for prescribing (according to the class of

functional movements). A. for the output, we obtain time history of the generalised coordinates, velocities of the drives, the torque-rpm diagram for each actuator, and the total energy consumed.

CHAPTER IV

THE PROGRAM MODULES

4.1 INTRODUCTION:

The simulation algorithm described in the previous chapter is implemented on a DEC 1090 mainframe in an interactive, user friendly environment.

In one session, the user can set the input data, run the simulation routine and obtain the results on a VDU, a graphic terminal or the line printer, and save the output on the disk for future reference. If not satisfied with the results, the user may change any of the input parameters on line using the Editor routine, and rerun the Simulator routine. To effect the above actions is the Command Interpreter routine, which accepts commands from the user, decodes it, and performs the necessary action. The commands are arranged in a hierarchial fashion with three levels. Errors, if any, resulting either from user action or during the program run are trapped, and relevant warnings or messages given to the user.

4.2 THE PROGRAM MODULES:

The program consist of four main modules. These will now be discussed in detail.

4.2.1 Block Matrix Operator :

This module consists of a number of procedures which define all the vector, matrix and block matrix operations necessary for the simulation algorithm. Let us use the following notation to describe the vectors, matrices, and block matrices:

VEC-3D	A vector of dimension 1X3
VEC-ND	A vector of dimension 1XN
MAT-3D	A matrix of dimension 3X3
MAT-ND	A matrix of dimension NXN
BLK-V-V	A block vector of dimension 1XN, whose elements are of type VEC-3D
BLK-V-M	A block vector (1XN) with elements of type MAT-3D
BLK-M-V	A block matrix (NXN) with elements of type VEC-3D
BLK-M-M	A block matrix (MXN) with elements of types MAT-3D
BLK-V-V-V	A block matrix (1X2) with elements of type BLK-V-V
BLK-V-M-V	A block matrix (1X2) with elements of type BLK -M-V
BLK-M-M-M	A block matrix (2X2) with elements of type BLK-M-M.

An operation is named based on the type of the output variable. For instance, if a procedure takes two entities of type MAT-ND and after performing operations returns an entity of type MAT-ND, it will be named as OPN-MND. Simularly, if a procedure returns an entity of type BLK-M-M, it will be named as OPN-M-M. However, for operations involving dot product of vectors, the keyword DPN will be used instead of OPN. For describing the operation, the following notation will be used:

< Operation > (< entity,entity..>: <entity type>;
< entity,entity..>: ...);

The following is the list of all the operations defined in this module. The last entity is always the output parameter.

i) OPN-V3D (OPCODE: integer; S: real ; A: MAT-3D;
B,C: VEC-3D; D: VEC-3D);

Here and in all further operations, OPCODE represents the operation code, whose value determines which operation is to be performed on the input parameters. In this case, the following operations are performed.

OPCODE	OPERATION
1	D = B+C
2	D = B−C
3	D = S.B
4	D = A.B

If the OPCODE is 1, then the vectors B and C are added according to the rules of the vector addition . Dummy variables may be passed for S and A. In this program, for dummy entities, a zero, or a null vector, or a null matrix, or a null block matrix is passed, depending upon the operations.

ii) OPN- VND (OPCODE: integer; S:real; A,B,C: VEC-ND);

In Pascal, unlike Fortran, all the variables used must be declared, and the type checking is done at compile time. Hence, OPN-V3D is seperated from OPN-VND, although the two differ only in the dimensions of the parameters. The OPCODE and the operations are exactly same as for i).

iii) OPN-M3D (OPCODE: integer; S: real; A,B,C; MAT-3D);

This is for doing operations on matrices. The Operations for the OPCODES are as follows

OPCODE	OPERATION
1	$C = A + B$
2	$C = A - B$
3	$C = A^T$
4	$C = S . A$
5	$C = A.. B$

This procedure is used, for instance, to calculate the transition matrix A_N in Eqn. 2.6 by repeatedly applying it. Further, it is used, along with OPN-V3D and OPN-VND, in almost all the operation that follow.

iv) OPN - MND (OPCODE : integer; S: real; A,B,C: MAT-ND);

This is same as OPN-M3D, except for the dimensions of the matrices A,B, and C, and the OPCODES have the same meaning. This procedure is called while evaluating the expressions in Eqn. 2.12 through 2.18. It is also called by some of the procedure that follow.

v) OPN1-V-V (OPCODE: integer; S:VEC-ND; A:BLK-M-V; B,C,D: BLK-V-V);

The operations performed by this procedure for different values of OPCODE is as follows

OPCODE	OPERATION
1	$D = B + C$
2	$D = B - C$
3	$D = S \cdot A$

It is easy to see that while performing the operation $D = B + C$, the elements of B are added to the corresponding elements of C . These elements are not numbers, but vectors. Hence, to calculate D, this procedure invokes OPN-V3D, N times. Also, in this case, dummy variables are passed as S and A.

vi) OPN2-V-V (A:BLK-V-M; B:BLK-M-V; C:BLK-V-V);

No OPCODE is given here as only one operation is to be performed, i.e.,

$$C = A \cdot B$$

An instance of the use of this operation is in Eqn. 2.19 for calculating D_i^1 and D_i^2 .

vii) OPN-M-V (OPCODE: integer; S: MAT-ND; A: BLK-M-M;
B,C,D:BLK-M-V);

The OPCODE and corresponding operations are as follows;

OPCODE	OPERATION
1	$D = B + C$
2	$D = B - C$
3	$D = B^T$
4	$D = S \cdot B$
5	$D = A \cdot B$

This procedure calls OPN-V3D repeatedly to evaluate D. Also, when OPCODE is 3, the transpose of B is evaluated, not the elements of B. This procedure is used in Eqn. 2.15 through 2.19 to evaluate the expressions.

viii) OPN-M-M (OPCODE: integer; S: MAT-ND; A,B,C: BLK-M-M) ;

This operates on block matrices whose elements are matrices, and is used for evaluating the block matrices B, D and C in Eqn. 2.13 through 2.18 and 2.21. The OPCODES and the corresponding operations are as follows:

OPCODE	OPERATIONS
1	$C = A + B$
2	$C = A - B$
3	$C = A^T$
4	$C = S . A$
5	$C = A . B$

Again, it should be noted that to evaluate C, the elements of A and the corresponding ones in B are operated by OPN-M3D repeatedly as the elements are not numbers but matrices.

ix) OPN1-V-V-V (S:VEC-ND; A:BLK-V-M-V; B:BLK-V-V-V);

As there is only one operation to be performed, OPCODE is not used. This does the operation

$$B = A . S$$

To evaluate expressions like $B\dot{q}$ and $D\dot{q}$ in Eqn. 2.12 and 2.16, this procedure is used.

x) OPN2-V-V-V (A,B,C: BLK-V-V-V);

This does the operation

$$C = A + B$$

Please note that as the elements of A and B are block matrices of type BLK-V-V, OPN-V-V is invoked repeatedly to evaluate C = A + B. This is used in Eqn. 2.16.

xi) OPN-V-M-V (A:BLK-V-M-V; B: BLK-M-M-M; C:BLK-V-M-V);

This is used in Eqn.2.23 and does the operation

$$C = B \cdot A$$

xii) DPN-R (A,B: VEC-3D; R: real);

This gives R as the dot product of two vectors A and B, and is used in the procedures that follow.

xiii) DPN-V (A: BLK-M-V;B:BLK-V-V; C:VEC-ND);

This performs the operation

$$C = B \cdot A$$

To do this, DPN-R is called repeatedly as the elements of B and A are vectors.

xiv) DPN1-M (A,B: BLK-M-V; C: MAT-ND) ;

This does the operation

$$C = A \cdot B$$

xv) DPN2-M (A,B: BLK-V-M-V; C:MAT-ND);

This does the operation

$$C = A \cdot B$$

by repeatedly applying DPN1-N to the elements of A and the corresponding ones of B and adding the matrices so obtained by OPN-MND.

There is also a procedure for calculating the inverse of a matrix.

xvi) INVERSE (DIM: integer; A,B: MAT-ND);

B is returned as the inverse of A. DIM is the dimension of the matrices A and B. This procedure is used to calculate the inverse of the Jacobian matrix, in Eqn. 3.5

4.2.2 Simulator :

This module implements the simulation algorithm described in the previous chapter. This again consists of seven main submodules.

The first submodule creates the link structures for storing the input data and initialises certain variables and files. The configurations parameters of the links of the manipulator are represented internally by means of a doubly linked circular list, and are accessed by means of

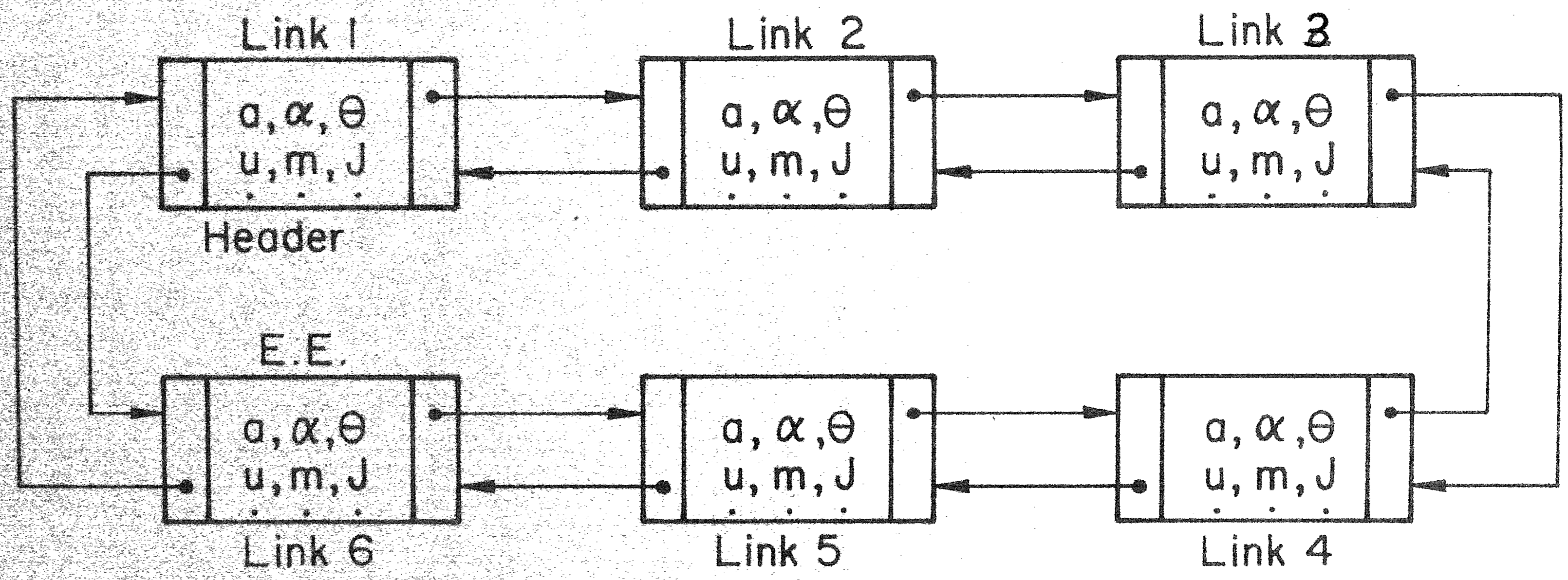


Fig.4.1 The link structure for representation of the manipulator configuration

a pointer, as shown in Fig. 4.1 . One node of the link is designated as the Header, and contains a record consisting of all the configuration parameters like linklength, link twist, mass, inertia, centre of gravity, etc. Also, the record contains two pointers, a left pointer pointing to the last link, and a right pointer pointing to the second link. In the same way, the left pointer of the second link contains the address of the pointer to the first link, and the right pointer, of the third. When the last link is reached its right pointer is linked to the first link. In the same manner, the generalised joint variable, q, velocity, $\dot{q}$ and the transition matrix A are stored in another link structure. The acceleration, in functional coordinates, describing the task of the manipulator, is stored as an array (for a series of time instants) of an array (for each dof).

Four input channels are initialised for reading from files TASK.DAT, CONFIG.DAT, CMND.DAT and PROG.HLP. The first two files obviously are for task and configuration data, The sets of commands used by the Command Interpreter are stored in CMND.DAT, and PROG.HLP contains help for the user, which can be accessed while the program is running. The output files POSE.DAT, POSTR.DAT, DRIVE.DAT and PNDIAG.DAT, for storing the data for internal coordinates,

external coordinates, drives, and the P-N diagram respectively, are also initialised. Global variables like unit matrices, unit block matrices, matrices E and V in Eqn. 2.13 and 2.15, null matrices, etc. are initialised. Certain option are also set to their default values. The system of units for both input and output data are set to MKS units, the representation for positioning and orientation are set to Cartesion and Euler respectively (Section 3.3)

The second part of this module forms and solves the geometric and the kinematic model. First, the functions λ and Λ(Eqn. 2.10) are defined in procedures LAMDA and BIG-LAMDA. Another function, LAMDASTAR is defined, which takes two indices i and j, and returns the matrix $\lambda(\rho_{i,j})$ (Eqn. 2.15). Next comes the procedure KINEMATIC. The geometric and kinematic modelling is done here. First the transition matrices are computed in the body fixed system, (Eqn.2.3) and then the matrices so obtained are concatenated to obtain the transition matrices in the external coordinate system. Next the block matrix B^o is evaluated (Eqn.2.15). Now, the block matrix D^o is evaluated (Eqn. 2.19). Finally, internal velocities and accelerations are computed (Eqn. 2.14, 2.18).

The third submodule computes the Jacobian matrix and the vector A from the matrices B^o and D^o evaluated earlier. (Eqn. 3.4).

The fourth submodule is the adjustment block. The acceleration in functional coordinates are transformed into those in external coordinates, as discussed in Section 3.3.

Using the Jacobian matrix and the vector A obtained in submodule three, the accelerations in external coordinates obtained in submodule four are transformed into those in internal coordinates, in the submodule five.

The sixth submodule is for dynamic modelling. Eqn. 2.20 through 2.25 are used and the drives, at a time t, obtained. Also, the torque and rpm are calculated for each joint at this time instant, as well as the energy consumed since the time instant ($t-\Delta t$), from the Eqn. 3.14 and 3.17.

In the seventh submodule, the new state, q and $\dot{q}$ are computed by the integration of $\ddot{q}$ over the time interval Δt , and the time is incremented by Δt.

The first two main modules have now been discussed. But the user will really not be concerned with these two modules. To use the program, what he is interested in is the commands to be given, and the Editor.

4.2.3 Command Interpreter (CI):

This is for performing simulation, editing, input/ output, etc., as and when requested by the user. The commands are organised in a hierarchial fashion into three levels. The commands can be shortened until it becomes unique. If the command is misspelt, or an illegal command or an ambiguous command is given at any level, a message is given to the user, warning this. If a valid command is given then it is interpreted, and the control passed to the module required to perform the action desired.

At the top level, a double arrow'>>' is given as a prompt . Now the user can type in any of the following commands:

Command	Action
>> HELP	Give help for top level actions
>> TYPE INPUT	Display the input data on the terminal
>> LIST INPUT	List the input data on the line pinter
>> SIMULATE	Perform simulation
>> TYPE OUTPUT	Display the output data on the terminal
>> LIST OUTPUT	List the output data on the line pinter

>> PLOT	Plot the graphs on the graphics terminal.
>> EDIT	Edit the input data.
>> UPDATE	Update the input file.
>> DOCUMENT	Type the Documentation.
>> EXIT	Exit from the top level.

When any of the input, output or edit action are requested by the user, the CI in invoked recursively, and the user enters the second level. For input action, the second level prompt is a vertical line '|' . Now the user can type in any of the following commands:

| HELP	Type help for the input action commands.
| SYSTEM	Type the system of units, coordinates, etc.
| CONFIG	Type the configuration parameters of the manipulator.
| STATE	Type the state parameters of the manipulator.
| TASK	Type the task of the manipulator .
| EXIT	Exit this level.

For output action, the second level prompt is a forward slash '/'. The user may now type in any of the following commands:

/ HELP	Type help for output action commands.
/ DRIVE	Display the drives in the joints.
/ ORIENT	Display the joint orientation .
/ POSITION	Display the joint positions .
/ VELOCITY	Display the joint velocities.
/ ACCELER	Display the joint accelerations.
/ PM DIAG	Display the P-M diagram.
/ ENERGY	Display the energy consumed.
/ EXIT	Exit this level.

For PLOT action, the second level prompt is a back slash '\' . The commands are same as for output actions.

For performing editing of the input data, when the EDIT command is given, then the user enters the second level. The prompt is a percent sign'%' . Now the following commands can be given :

% HELP	Type help for edit action.
% SYSTEM	Change system of units,representation of coordinates etc.
% CONFIG	Edit configuration parameters.
% STATE	Edit state parameters.
% TASK	Edit manipulator task.
% EXIT	End edit.

When one of the SYSTEM,CONFIG,STATE, or TASK command is given, the CI is once again called recursively, and the user thus inters the third level. The prompt is an asterix '*'. If the user typed the SYSTEM command, the Editor asks for the system parameter to be changed. The user can now give the following answers:

* System Parameter : UNITS
* System Parameter : ANGLE
* System Parameter : POSITION
* System Parameter : ORIENT

The command interpreter is now once again invoked to determine the system of UNITS (CGS,MKS or FPS), ANGLE (DEGREES or RADIANS), POSITION (CARTESIAN, CYLINDRICAL, or SPHERICAL), ORIENT (NONE, PARTIAL, FULL). If the system of orientation is partial or full , CI is again called to determine whether the functional coordinates are Euler angles, a vector and an angle, etc (as discussed in section 3.3). For instance,

* System of representation for Orientation: EULER.

In response to the CONFIG command, the editor gives the following prompt,

* Add node, delete node, or change node?

In response, the user can respond by typing ADD, DELETE, or CHANGE. If the CHANGE command is given, the editor asks for the number of the link whose link parameters are to be changed.

* Link Number:

The user can now typing a number (1 to N) for the link whose link parameters are to be changed . Now the C.I. is called to determine the particular parameter to be changed. The following commands can be given :

* Link parameter : LINKTYPE

* Link parameter : LINKLENGTH

* Link parameter : LINKTWIST

* Link parameter : JOINTDIST

* Link parameter : COG

* Link parameter : MASS

* Link parameter : INERTIA

* Link parameter : REDUCT

* Link parameter : EFF

After this, the user can type in the new values, and the corresponding changes will be made.

If the DELETE command is given, then the Editor asks for the number of the link to be deleted, and deletes that link. Similarly, for an ADD command, a number K is taken, and a new link added after the Kth link.

If the state parameters are to be edited, then the second level Editor command STATE can be given.

% STATE

Now the C.I. is invoked (third level) to determine the state parameter to be changed.

* State Parameter:

Now the following commands may be given :

* State parameter : INITIAL VELOCITY

* State parameter : INITIAL POSIT

Now the vectors may be typed in as directed by the editor. Similarly, by issuing the second level % TASK command, the task parameters may be changed. The editor takes a number K from the user and changes the acceleration vector at the Kth time instant.

The user may make as many changes as the desires, then exit the editor module. Now the top level command SIMULATE may be given to rerun the simulation module. Now, the output parameters may be observed and evaluated. If the user is satisfied with the results, then he may issue the UPDATE command, which will update the input files CNFG.DAT and TASK.DAT. This cycle the user may continue as many times as he desires.

All the valid commands to the CI are stored in the file CMND.DAT as sets of commands. When the CI is called, a parameter is passed to it indicating which set of commands it should accept from the user. In a command set, for each command coreesponds an action to be performed. The action for a particular command may include a call to the CI. By making such recursive calls to the CI, a hierarchial command structure is built. Control can pass to the higher level only after the lower level releases the CI. Such a structure allows new commands to be easily incorporated at any level, to cater to new modules which may be added to the program.

4.2.4 Editor Module:

The editor may be called from the top level to interactively edit any of the input parameters. After editing the new input parameters may be saved by updating the file. All the Edit mode commands are described in Section 4.2.3.

Apart from the above four main modules the program also contains two other small modules: The HELP module for giving help to the user at various levels, and the UTILITY module which contains utility routines for performing certain actions which, though not directly related to the actual running of the program, help to make it more useable.

There are standard procedures for reading integers and reals from a device. Suppose the program is waiting for the user to give an real number from the terminal. If by mistake the user types an integer, or some character, the program is interupted, and control returned to the monitor. To avoid this, two procedures, READIN, and READRL are written, which dont read the numbers directly, but as a sequence of characters which are converted into their ASCII code and then the number computed.

The whole program, except for the plotting routine is written in Pascal. The plotting routine, which calls certain routines from the Interactive, Graphics Library, PLOT-10, is written in Fortran, as these routines are only Fortran-Callable. The object code for the plotting routine and the rest of the program is linked together using the Fortran I/O Link Facility, FTNLNK, available here on DEC 10.

4.3 SETTING INPUT DATA:

The data regarding the configuration, state, or task of the manipulator are initially given through disk files. These parameters may later be edited from the terminal.

The data for the configuration of the manipulator is given in the file CNFG . DAT in the following format:

NO OF LINKS

GRAVITY FORCE VECTOR

LINKTYPE/LINK LENGTH/LINK TWIST /JOINT ANGLE or
JOINT DISTANCE

COG VECTOR

MASS

INERTIA TENSOR

EXTERNAL FORCE VECTOR

EXTERNAL MOMENT VECTOR

REDUCTION RATIO/ JOINT EFFICIENCY

A blank line or comment

LINKTYPE/LINKLENTH /LINK TWIST/ JOINT ANGLE or
JOINT DISTANCE

COG VECTOR

.

.

.

(for N links)

The LINKTYPE is given as 'R' for a revolute joint, and 'P' for a prismatic joint. The COG vector is given as (ρ_1 ρ_2 ρ_3), and the inertia tensor J as (J_{11} J_{12} J_{13} J_{22} J_{23} J_{31}). In this way, the data for N links are given.

The data for the task of the manipulator, and the initial state are given in the file tASK.DAT in the following formate :

INITIAL POSITION VECTOR

INITIAL VELOCITY VECTOR

A blank line or comment

FUNCTIONAL COORDINATES ACCELERATION

FUNCTIONAL COORDINATES ACCELERATION

.

.

.

FUNCTIONAL COORDINATES ACCELERATION

All these vectors are of the dimensions (1XN) . The units for these values can be given in either MKS or CGS or FPS units. By default, MKS system of units is assumed.

4.4 RUNNING THE PROGRAM:

To start the program, the following monitor command is given

.RUN ROBOTA

Now the control is passed to the top level CI and the flow of execution will now totally depend upon the commands given by the user.

CHAPTER V

RESULTS, CONCLUSIONS AND SUGGESTIONS

5.1 RESULTS :

The program is run on a DEC - 10 computer using a sample input data. The input and output data, together with the transactions in a single session are listed in Appendix A 1. The listing illustrates some of the facilities provided by the Editor. Also appendend with it are the drive time, state time, and torque-rpm graphs. The output data obtained agrees with the actual values computed manually. The program listing is given in Appendix A 2.

5.2 CONCLUSIONS:

As pointed out earlier, an algorithm which calculates the dynamic characteristics of a manipulator during the execution of a task clearly represents a useful means for the process of manipulater design. The algorithm chosen for this work forms and solves the dynamic model of the manipulator, and using incremental iterative displacement technique, computes the dynamic characteristics at a series of time instants. The dynamic model is based on the general theorem of Dynamics, and uses block matrix formalism to reduce the complex analytical equations into a compact form suitable for solving on a computer. The

inputs to the algorithm are the manipulator configuration (described by a set of parameters defining the geometric and inertial properties of the link), the initial state, and the manipulation task (in the form most suited for prescribing, according to the class of the functional movements). As the output, we obtain the time history of the generalised coordinates, velocities and drives, the P-N diagram, and the total energy consumed.

This algorithm is implemented in the increasingly popular Pascal language, to aid the designer in a fast analysis of the dynamic characteristics of a number of manipulator configuration. The P-N diagram can be used to give specifications for the actuator units. The total energy consumed for a particular task can be compared for different configurations and the configuration chosen accordingly. The various graphs can be viewed on a graphics terminal.

Any of the input parameters can be changed, by means of the Editor module and simulation done again. Further, the data may be given in any units. The program is command driven, i.e. the user types in commands for the action he desires. The command is decoded, and the action taken, by the Command Interpreter module . The Editor and

the Command Interpreter thus allow the user to analyse different configurations in an interactive manner. Further the structured development of the program allows new modules to be easily added.

6.3 SUGGESTIONS:

Improvements in the program can be made in two ways. One is an extension of the Dynamic module to include a manipulator with third and fourth class pairs, and a branched structure, and a manipulator with elastic segments . Secondly, other modules can be added to consider other problems in Robotics, like path synthesis, workspace synthesis actuator modelling , performance evaluation, etc. If this is done, coupled with the extensive use of computer graphics, then the gap between the designers and theoreticians can be bridged.

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APPENDIX A - I

```
        OPSER TRANSACTION LOG
        IIT KANPUR 503A(2)          10-04-83
7-MAY-85         02:35:33           Job 23  [13100,130461]
*RU K 100K
        [2:35:40]
        *
*
*C
        >> STOP AT MAIN BEGIN
        >> type ? for help
        >>
*C
        < Continue , Skip or Quit > :
*C
        This is an interactive,user friendly,program,which can be used
        or the design of Robotic Manipulators by the simulation of its dynam
        nd other characteristics.The program was developed by Madhu Shekhar
        nder the guidance of Dr.B.Sahay.
        For complete help see the DOCUMENTATION.
        >>
*HELP
        The following is a summary of commands
        ------------------------------------------
        HELP               : type this text
        TYPE INPUT         : type input parameters
        LIST INPUT         : list input parameters
        SIMULATE           : simulate manipulator dynamics
        TYPE OUTPUT        : type output parameters
        LIST OUTPUT        : list output parameters
        PLOT               : plot graphs on graphics tty
        EDIT               : edit input parameters
        UPDATE             : update input file
        DOCUMENT           : type the documentation
        EXIT               : end execution
        >>
*TYPE U
        >> Illegal command
        >>
*TYPE INP
        !
*HELP
        The commands are
        ----------------
        HELP               : type this text
        SYSTEM             : display system of units,config,etc.
        CONFIG             : display configuration parameters
        STATE              : display manipulator state
        TASK               : display manipulator task
        EXIT               : end
```

APPENDIX A - 1

```
        USER TRANSACTION LOG
        IIT KANPUR 503A(2)          10-04-83

7-MAY-85          02:35:35          Job 23  [13100,130461]
*RU K 100K
        [2:35:40]
        *

*
*C
        >> STOP AT MAIN BEGIN
        >> type H for help
        >>
*C
        < Continue , Skip or Quit > :
*C
        This is an interactive,user friendly,program,which can be used
        or the design of Robotic Manipulators by the simulation of its dyna:
        nd other characteristics.The program was developed by Madhu Shekhar
        nder the guidance of Dr.B.Sahay.
        For complete help see the DOCUMENTATION.
        >>
*HELP
        The following is a summary of commands
        ----------------------------------------
        HELP                : type this text
        TYPE INPUT          : type input parameters
        LIST INPUT          : list input parameters
        SIMULATE            : simulate manipulator dynamics
        TYPE OUTPUT         : type output parameters
        LIST OUTPUT         : list output parameters
        PLOT                : plot graphs on graphics tty
        EDIT                : edit input parameters
        UPDATE              : update input file
        DOCUMENT            : type the documentation
        EXIT                : end execution
        >>
*TYPE U
        >> Illegal command
        >>
*TYPE INP
        !
*HELP
        The commands are
        ----------------
        HELP                : type this text
        SYSTEM              : display system of units,config,etc.
        CONFIG              : display configuration parameters
        STATE               : display manipulator state
        TASK                : display manipulator task
        EXIT                : end
```

```
         |
*SYSTEM
         Input data          :  MKS
         Output data         :   MKS
         Angle               :   DEGREES
         Positioning of EE          :  CARTESIAN
         Orientation of EE          :  EULER
         |
*CONFIG
         This manipulator is an open chain active mechanism with 4 degrees
         of freedom
         < Continue , Skip or Quit > :
*C
         Link  1
         ---------
         LINKTYPE            : Revolute
         LINKLENGTH          :    0.00000
         LINKTWIST           :   90.00000
         JOINTDIST           :    0.76500
         JOINTANGLE          : variable
         RHO                 :    0.00000
                                 -0.67499
                                  0.01499
         MASS                :   95.99000
         INERTIA             :   33.72399        0.00000        0.00000
                                  0.00000        2.87900        0.60900
                                  0.00000        0.60900       33.05500
         REDUCT. RATIO       :  100.00000
         EFFICIENCY          :    0.85000
         < Continue , Skip or Quit > :
*C
         Link  2
         ---------
         LINKTYPE            : Revolute
         LINKLENGTH          :    0.00000
         LINKTWIST           :  -90.00000
         JOINTDIST           :    0.00000
         JOINTANGLE          : variable
         RHO                 :    0.00000
                                  0.01000
                                 -0.20300
         MASS                :   82.60999
         INERTIA             :    3.99000        0.00000        0.00099
                                  0.00000        3.78599       -1.53999
                                  0.00099       -1.53999        1.47499
         REDUCT. RATIO       :  100.00000
         EFFICIENCY          :    0.85000
         < Continue , Skip or Quit > :
*C
         Link  3
         ---------
         LINKTYPE            : Revolute
         LINKLENGTH          :   -0.03500
         LINKTWIST           :   90.00000
         JOINTDIST           :    0.51000
         JOINTANGLE          : variable
         RHO                 :    0.02900
                                 -0.52400
                                 -0.00700
```

```
             MASS             :    52.90000
             INERTIA          :     8.29500        0.17799       -0.01200
                                    0.17799        0.42500        0.19500
                                   -0.01200        0.19500        8.23699
             REDUCT. RATIO    :   100.00000
             EFFICIENCY       :     0.85000
             < Continue , Skip or Quit > :
      *C
             Link  4
             ---------
             LINKTYPE         :  Revolute
             LINKLENGTH       :     0.00000
             LINKTWIST        :   -90.00000
             JOINTDISP        :     0.00000
             JOINTANGLE       :  Variable
             RAD              :    -0.00100
                                    0.02399
                                    0.00200
             MASS             :    13.33999
             INERTIA          :     0.15000        0.00000       -0.00099
                                    0.00000        0.06199        0.00099
                                   -0.00099        0.00099        0.15000
             REDUCT. RATIO    :   109.99999
             EFFICIENCY       :     0.85000
             < Continue , Skip or Quit > :
      *C
             !
      *STA
             JOINT                      JOINT ANGLE            JOINT VELOCITY
      ---------------------------------------------------------------------------
             JOINT  1                     29.9999                 0.0000
             JOINT  2                     59.9999                 0.0000
             JOINT  3                    -25.0000                 0.0000
             JOINT  4                     10.0000                 0.0000
             !
      *TASK
             TIME                   JOINT1       JOINT2       JOINT3       JOINT4
      -------------------------------------------------------------------------------
             0.00                   0.421       -0.259        0.505        0.000
             0.10                   0.447       -0.255        0.508        0.000
             0.20                   0.490       -0.263        0.494        0.000
             0.30                   0.557       -0.266        0.485        0.000
             0.40                   0.624       -0.250        0.455        0.000
             0.50                   0.702       -0.223        0.414        0.000
             0.60                   0.842       -0.247        0.364        0.000
             0.70                   1.027       -0.127        0.383        0.000
             0.80                   1.146       -0.064        0.266        0.000
             0.90                   1.255        0.049        0.135        0.000
             1.00                   1.192        0.083       -0.098       47.555
             1.09                   1.155       -0.000       -0.295       47.555
             1.19                   1.192        0.108       -0.396       48.701
             < Continue , Skip or Quit > :
      *C
             1.29                   1.217        0.085       -0.483       48.701
             1.39                   1.329        0.153       -0.626       72.193
             1.49                   1.362        0.276       -0.536       74.484
```

```
          1.59          1.458      0.456     -0.530     74.484
          1.69          1.515      0.558     -0.424     75.630
          1.79          1.552      0.737     -0.278     64.744
          1.89          1.659      0.881      0.171     57.869
          1.99          1.640      1.519      0.315     54.431
          2.09          1.244      1.711      0.377     48.701
          2.19          0.936      2.079      0.292     53.285
          2.29          0.500      1.974      0.344     51.566
          2.39          0.176      1.790      0.373     52.712
          2.49         -0.171      1.485      0.641      0.000
          2.59         -0.385      1.234      0.515      0.000
          2.69         -0.610      1.012      0.571      0.000
          2.79         -0.681      0.711      0.602      0.000
          2.89         -0.931      0.438      0.706      0.000
          2.99         -0.898      0.172      0.530    -36.669
          3.09         -0.831     -0.169      0.581    -36.669
          < Continue , Skip or Quit > :
*C
          3.19         -0.830     -0.236      0.533    -34.950
          3.29         -0.828     -0.264      0.507    -35.523
          3.39         -0.474     -0.146      0.289    -31.512
          3.49         -0.480     -0.123      0.299    -31.512
          3.59         -0.426     -0.215      0.313    -31.512
          3.69         -0.313     -0.140      0.251      0.000
          3.79         -0.304     -0.128      0.268     41.253
          3.89         -0.222     -0.076      0.223     41.253
          3.99         -0.036     -0.424      0.200     36.096
          4.09         -0.011     -0.473      0.198     37.242
          4.19          0.026     -0.555      0.495      0.000
          4.29          0.048     -0.603      0.194      0.000
          4.39          0.067     -0.569      0.151      0.000
          4.49          0.066     -0.533      0.127      0.000
          4.59          0.037     -0.476      0.430      0.000
          4.69          0.039     -0.472      0.414     -6.875
          4.80         -0.069     -0.336      0.124    -63.025
          4.90         -0.295     -0.106     -0.036    -63.025
          I
*C
*Q
*EXIT
          >>
*E
          >> Ambiguous command
          >>
*SIM
          >> Simulation going on. Please wait.
          ENERGY CONSUMED =    95.573
          >>
*TYPE OUT
```

```
/
*HELP
        The commands are
        ----------------
        HELP               : type this text
        DRIVE              : display drives in joints
        POSITION           : display joint positions
        VELOCITY           : display joint velocity
        ACCELERATION       : display joint accelerations
        TW DIAG            : display Torque - Row diagram
        ENERGY             : display energy consumption for task
        EXIT               : end output parameters display
/
*DEIV
/ Illegal command
/
*DRIV
< Continue , Skip or Quit > :
*C
```

The history of the drives in the joints

Time	Joint1	Joint2	Joint3	Joint4
0.00000	9.55060	3.64174	7.80998	11.79779
0.10000	10.13568	3.37355	8.16534	13.22939
0.20000	10.54909	3.59292	8.82234	14.13576
0.30000	11.51070	4.59031	10.55959	16.00588
0.40000	12.93061	5.84052	12.89729	18.80216
0.50000	14.20627	7.20770	15.36202	21.52978
0.60000	15.82987	8.95493	18.30108	24.80651
0.70000	21.82093	14.91414	26.11008	33.16501
0.80000	25.58384	17.03153	29.72158	39.68996
0.90000	29.12713	20.28629	40.33538	51.39901
1.00000	31.14123	25.13596	44.33157	56.33195
1.09999	25.95434	19.57750	35.10080	44.95842
1.19999	28.36542	24.11999	36.58231	43.56161

< Continue , Skip or Quit > :

*C

1.29999	24.25456	19.21517	29.13220	37.16195
1.39999	23.59442	19.22044	28.42454	35.44696
1.49999	7.66969	3.66944	11.34444	18.53908
1.59999	7.57853	3.15075	12.29243	20.63906
1.69999	0.00000	-4.28888	2.01106	11.47763
1.79999	0.00000	-1.89722	-2.22520	6.24182
1.89999	0.00000	0.26757	-8.50038	-0.96956
1.99999	0.00000	5.55596	-14.86875	-13.68196
2.09999	-7.77058	-2.64225	-30.54229	-29.37927
2.19999	-4.84439	-0.44215	-25.69700	-23.63564
2.29999	-5.35187	-3.38068	-21.87200	-17.18837
2.39999	-3.84949	-2.22874	-16.04950	-11.94049
2.49999	-3.71529	-2.26640	-11.94905	-8.54431
2.59999	-4.34833	1.14603	-10.78065	-12.85998
2.69999	-6.02493	-0.18495	-9.68597	-12.55422
2.79999	-9.20560	-0.97751	-7.34047	-13.03264
2.89999	-11.47834	-2.73927	-6.53007	-12.99388

2.99999	-15.75373	-2.45141	-4.16558	-15.68716
3.09999	-17.59535	-3.97694	-9.54081	-21.70837

< Continue , Skip or Quit > :

*C

3.19999	-11.73260	2.57790	-6.55620	-20.09090
3.29999	-12.15186	2.26903	-6.47879	-20.27433
3.39999	-12.05698	2.40968	-5.57997	-19.51913
3.49999	-5.20023	1.71538	-0.77035	-7.89881
3.59999	-5.01590	1.88652	-0.71155	-7.77182
3.69999	0.00000	7.53746	2.05727	-5.09085
3.79999	0.00000	5.21749	0.91679	-3.47642
3.89999	0.00000	5.14803	1.05359	-3.06064
3.99999	0.00000	3.57904	1.52580	-0.73309
4.09999	10.29151	12.48175	3.30452	1.78230
4.19999	9.33372	12.02511	3.30478	2.58656
4.29999	11.07205	13.19690	5.68054	4.59176
4.39999	12.22592	14.35094	7.28044	6.41320
4.49999	13.09303	14.81743	10.54045	10.40493
4.59999	14.92292	16.12491	12.66084	13.21586
4.69999	17.27947	18.53640	15.91539	16.71283
4.80000	23.16658	24.06246	22.67859	24.09634
4.90000	27.35844	28.16228	29.04551	30.58532
5.00000	28.42389	26.42529	31.19131	35.99200

< Continue , Skip or Quit > :

*C

/

*ACC

< Continue , Skip or Quit > :

*C

Time history of the acceleration in the joints

Time	Joint 1	Joint 2	Joint 3	Joint 4
0.00000	0.90000	-1.00000	0.00000	0.00000
0.10000	0.95000	-1.12000	0.00000	0.00000
0.20000	0.95000	-1.14000	0.00000	0.00000
0.30000	0.97999	-1.14000	0.00000	0.00000
0.40000	1.02000	-1.17000	0.00000	0.00000
0.50000	1.02000	-1.17000	0.00000	0.00000
0.60000	1.02000	-1.17000	0.00000	0.00000
0.70000	1.25000	-1.17999	0.00000	0.00000
0.80000	1.29999	-1.45000	0.00000	0.00000
0.90000	1.29999	-1.50000	1.21000	0.00000
1.00000	1.34999	-1.51000	1.22999	0.00000
1.09999	0.92000	-1.15000	1.22999	0.82999
1.19999	0.92000	-0.70000	1.10999	0.82999
1.29999	0.73999	-0.70000	1.09999	0.85000

< Continue , Skip or Quit > :

*C

1.39999	[illegible]	-0.45000	0.92000	0.85000
1.49999	0.23000	-0.34000	0.91000	1.26000
1.59999	0.24000	-0.33000	0.85000	1.29999
1.69999	0.00000	-0.33000	0.82000	1.29999
1.79999	0.00000	-0.10000	0.75000	1.32000
1.89999	0.00000	0.10000	0.80000	1.12999
1.99999	0.00000	0.91000	0.83999	1.01000
2.09999	-0.75000	0.95000	0.00000	0.95000
2.19999	-0.71999	0.86000	0.00000	0.85000
2.29999	-1.25000	0.53999	0.00000	0.92999
2.39999	-1.25000	0.53999	0.00000	0.90000
2.49999	-1.25000	0.53999	0.00000	0.92000
2.59999	-1.17999	1.07000	-0.51999	0.00000
2.69999	-1.21999	1.07000	-0.65000	0.00000
2.79999	-1.32000	1.31000	-0.65000	0.00000
2.89999	-1.32000	1.31000	-0.65000	0.00000
2.99999	-1.65000	1.82000	-0.65000	0.00000
3.09999	-1.65000	1.82000	-1.34999	-0.64000
3.19999	-1.02000	1.90000	-1.34999	-0.64000

< Continue , Skip or Quit > :

*C

3.29999	-1.02000	1.90000	-1.34999	-0.61000
3.39999	-1.00000	1.90000	-1.25000	-0.61999
3.49999	-0.51999	1.09999	-0.45000	-0.55000
3.59999	-0.51999	1.09999	-0.45000	-0.55000
3.69999	0.00000	1.09999	-0.30000	-0.55000
3.79999	0.00000	0.81000	-0.30000	0.00000
3.89999	0.00000	0.81000	-0.30000	0.71999
3.99999	0.00000	0.61999	-0.15000	0.71999
4.09999	1.15000	0.51000	-0.15000	0.63000
4.19999	1.15000	0.50000	-0.15000	0.65000
4.29999	1.29999	0.50000	0.00000	0.00000
4.39999	1.40000	0.50000	0.00000	0.00000
4.49999	1.40999	0.45000	0.61999	0.00000
4.59999	1.45000	0.40000	0.63000	0.00000
4.69999	1.48999	0.40000	0.58000	0.00000
4.80000	1.71999	0.35000	0.50000	-0.12000
4.90000	1.71999	0.35000	0.50000	-1.09999
5.00000	1.50000	0.00000	0.50000	-1.09999

/

*C

/ Illegal command

/

*VEL

< Continue , Skip or Quit > :

*C

Time history of the velocities in the joints

Time	Joint 1	Joint 2	Joint 3	Joint 4
0.00000	0.09000	-0.10000	0.00000	0.00000

```
      0.10000          0.18500         -0.21200         0.00000          0.00000
      0.20000          0.28000         -0.32600         0.00000          0.00000
      0.30000          0.37800         -0.44000         0.00000          0.00000
      0.40000          0.48000         -0.55700         0.00000          0.00000
      0.50000          0.58200         -0.67400         0.00000          0.00000
      0.60000          0.68400         -0.79100         0.00000          0.00000
      0.70000          0.83900         -0.90900         0.00000          0.00000
      0.80000          0.93899         -1.05400         0.00000          0.00000
      0.90000          1.05900         -1.20400         0.12100          0.00000
      1.00000          1.20400         -1.35500         0.24399          0.00000
      1.09999          1.29600         -1.47000         0.36699          0.08299
      1.19999          1.38800         -1.54000         0.47800          0.16599
      1.29999          1.46200         -1.61000         0.58799          0.25099
      < Continue , Skip or Quit > :
*C

      1.39999          1.53200         -1.66500         0.68000          0.33599
      1.49999          1.55500         -1.68900         0.77099          0.46200
      1.59999          1.57900         -1.72200         0.85599          0.59200
      1.69999          1.57900         -1.75500         0.93799          0.72200
      1.79999          1.57900         -1.76500         1.01299          0.85400
      1.89999          1.57900         -1.75500         1.09299          0.96699
      1.99999          1.57900         -1.66400         1.17700          1.06800
      2.09999          1.50400         -1.55800         1.17700          1.16300
      2.19999          1.43200         -1.48200         1.17700          1.24799
      2.29999          1.30700         -1.42800         1.17700          1.34099
      2.39999          1.18200         -1.37400         1.17700          1.43099
      2.49999          1.05700         -1.32000         1.17700          1.52300
      2.59999          0.93900         -1.21300         1.12500          1.52300
      2.69999          0.81700         -1.10600         1.06000          1.52300
      2.79999          0.67500         -0.97500         0.99500          1.52300
      2.89999          0.53300         -0.84400         0.93000          1.52300
      2.99999          0.36800         -0.66200         0.86500          1.52300
      3.09999          0.20300         -0.48000         0.73000          1.45900
      3.19999          0.10100         -0.29000         0.59500          1.39500
      < Continue , Skip or Quit > :
*C

      3.29999         -0.00099         -0.10000         0.46000          1.33400
      3.39999         -0.10099          0.08999         0.33500          1.27199
      3.49999         -0.15299          0.19999         0.29000          1.21700
      3.59999         -0.20499          0.30999         0.24500          1.16200
      3.69999         -0.20499          0.41999         0.21500          1.10700
      3.79999         -0.20499          0.50099         0.18500          1.10700
      3.89999         -0.20499          0.58199         0.15500          1.17900
      3.99999         -0.20199          0.64399         0.14000          1.25100
      4.09999         -0.08999          0.69499         0.12500          1.31400
      4.19999          0.02500          0.74499         0.11000          1.37900
      4.29999          0.15500          0.79499         0.11000          1.37900
      4.39999          0.29500          0.84499         0.11000          1.37900
      4.49999          0.43600          0.88999         0.17200          1.37900
      4.59999          0.58100          0.92999         0.23500          1.37900
      4.69999          0.73000          0.96999         0.29300          1.37900
      4.80000          0.90200          1.00499         0.34300          1.36700
      4.90000          1.07400          1.03999         0.39300          1.25700
```

```
     5.00000          1.22100          1.03999          0.44300          1.14700
     /
*C

     / illegal command
     /
*
*PD

     < Continue , Skip or Quit > :
*C

               The PT diagram
               --------------

     JOINT 1
     -------

          RPM              TORQUE

     85.91099           0.08118
     176.55519           0.08666
     267.37199           0.08966
     360.95219           0.09784
     458.35203           0.10991
     555.75183           0.12075
     653.15158           0.13455
     772.51109           0.18547
     896.55110           0.21831
     1020.75810           0.24758
     1119.69959           0.29020
     < Continue , Skip or Quit > :
*C

     1237.55040           0.22061
     1325.40121           0.24110
     1396.05380           0.20616
     1462.90680           0.20055
     1484.85950           0.06519
     1507.78713           0.06441
     1507.78713           0.00000
     1507.78713           0.00000
     1507.78713           0.00000
     1507.78713           0.00000
     1436.16962          -0.06604
     1367.41682          -0.04117
     1248.05434          -0.04549
     1128.69183          -0.03272
     1009.32933          -0.03158
     896.55113          -0.03696
     780.15333          -0.05121
     644.55753          -0.07824
     508.95173          -0.09756
     < Continue , Skip or Quit > :
*C
```

```
          351.10324          -0.13340
          193.94974          -0.15041
          96.94494          -0.09972
          -0.95485          -0.10340
          -96.94485          -0.10256
          -190.03963          -0.05270
          -195.75445          -0.05113
          -195.75445           0.00000
          -195.75445           0.00000
          -195.75445           0.00000
          -195.75445           0.00000
          -85.94095           0.08750
          23.87253          0.08401
          148.00954           0.09411
          281.59554           0.10392
          416.33544           0.11129
          554.79593           0.12599
          697.07702           0.14687
          861.31982           0.19691
          < Continue , Skip or Quit > :
*C

          1025.55261           0.23263
          1168.79764           0.24160
          < Continue , Skip or Quit > :
*C

          JOINT 2
          -------

             RPM              TORQUE
          -95.78999          0.03095
          -202.43879           0.02867
          -311.29739           0.03053
          -420.15599           0.03901
          -531.87929           0.04964
          -643.60259           0.06126
          -755.32590           0.07611
          -868.00409           0.12677
          -1.006E+03           0.14476
          -1.149E+03           0.17243
          -1.293E+03           0.21365
          -1.403E+03           0.16640
          -1.470E+03           0.20501
          < Continue , Skip or Quit > :
*C

          -1.537E+03           0.16332
          -1.580E+03           0.16337
          -1.612E+03           0.03136
          -1.644E+03           0.02678
          -1.675E+03          -0.03645
          -1.685E+03          -0.01612
          -1.675E+03           0.00227
          -1.588E+03           0.04722
          -1.497E+03          -0.02245
```

```
-1.415E+03        -0.00375
-1.353E+03        -0.02873
-1.312E+03        -0.01594
-1.250E+03        -0.01926
-1.158E+03         0.00974
-1.056E+03        -0.00156
-931.02753        -0.00830
-805.93563        -0.02328
-632.14433        -0.02083
-455.33233        -0.03382
< Continue , Skip or Quit > :
*C

-275.92104         0.02191
-95.49004          0.01928
85.94035          0.02048
190.97995          0.01483
295.01891          0.01603
401.05794          0.06406
478.40484          0.04434
555.75171          0.04375
611.95554          0.03042
663.55545          0.10609
711.40043          0.10221
759.14543          0.11217
805.89042          0.12198
849.86093          0.12594
888.05693          0.13706
926.25293          0.15755
959.67442          0.20453
993.09592          0.23937
993.09592          0.22461
< Continue , Skip or Quit > :
*C

< Continue , Skip or Quit > :
*C

JOINT 3
-------

   RPM          TORQUE

0.00000         0.06638
0.00000         0.05940
0.00000         0.07498
0.00000         0.08975
0.00000         0.10962
0.00000         0.13057
0.00000         0.15555
0.00000         0.22193
0.00000         0.25263
115.54290          0.34285
232.99560          0.37681
350.44830          0.29835
455.44221          0.31094
```

```
                < Continue , Skip or Quit > :
   *C

                561.36121          0.24762
                619.33202          0.21160
                736.22791          0.09642
                817.39442          0.10448
                895.59523          0.01709
                957.31371         -0.01891
               1043.70573         -0.07225
               1123.91732         -0.12638
               1123.91732         -0.25960
               1123.91732         -0.21842
               1123.91732         -0.18591
               1123.91732         -0.13642
               1123.91732         -0.10156
               1074.26252         -0.09163
               1012.10402         -0.08233
                953.12552         -0.06239
                888.05702         -0.05559
                825.93851         -0.03540
                697.07702         -0.08109
                < Continue , Skip or Quit > :
   *C

                568.15552         -0.05572
                439.25102         -0.05506
                319.39152         -0.04742
                276.02102         -0.00654
                233.95052         -0.00604
                205.30351          0.01748
                176.55652          0.00779
                148.00952          0.00904
                133.68502          0.01296
                119.36252          0.02808
                105.03902          0.03234
                105.03902          0.04828
                105.03902          0.06188
                164.21282          0.08959
                224.40152          0.10761
                279.78572          0.13528
                327.53073          0.19276
                375.27573          0.24688
                423.02073          0.26512
                < Continue , Skip or Quit > :
   *
   *C

                < Continue , Skip or Quit > :
   *C

                JOINT 4
                -------

                    RPM             TORQUE
                0.00000            0.09116
```

```
0.00000          0.10222
0.00000          0.10923
0.00000          0.12358
0.00000          0.14528
0.00000          0.15636
0.00000          0.19168
0.00000          0.25627
0.00000          0.30669
0.00000          0.39717
0.00000          0.43529
87.18236          0.38740
173.36473          0.33661
< Continue , Skip or Quit > :
*C

263.54738          0.28716
352.93103          0.27390
485.28017          0.14325
621.33087          0.15948
758.35157          0.08869
897.33305          0.04823
1015.72711        -0.00719
1121.81651        -0.10572
1221.60355        -0.22702
1310.88669        -0.18263
1408.57295        -0.13281
1503.10808        -0.09226
1599.74395        -0.06602
1599.74395        -0.09937
1599.74395        -0.09700
1599.74395        -0.10070
1599.74395        -0.10040
1599.74396        -0.12121
1532.51899        -0.16774
< Continue , Skip or Quit > :
*C

1465.29403        -0.15524
1401.22024        -0.15666
1335.09607        -0.15082
1278.32463        -0.06103
1220.55318        -0.06005
1162.78174        -0.03933
1162.78174        -0.02686
1238.40983        -0.02365
1314.03788        -0.00566
1380.21244         0.01377
1448.48781         0.01998
1448.48781         0.03548
1448.48781         0.04955
1448.48781         0.08040
1448.48781         0.10212
1448.48781         0.12914
1435.88311         0.18619
1320.34023         0.23634
1204.79734         0.27812
```

```
         < Continue , Skip or Quit > :
*C
         < Continue , Skip or Quit > :
*C
         /
*HEL
         The commands are
         ----------------
         HELP              : type this text
         DRIVE             : display drives in joints
         POSITION          : display joint positions
         VELOCITY          : display joint velocity
         ACCELERATION      : display joint accelerations
         RN DIAG           : display Torque - Rpm diagram
         ENERGY            : display energy consumption for task
         EXIT              : end output parameters display
         /
*ENERGY
         < Continue , Skip or Quit > :
*C
          Time history of the ENERGY consumption
         ----------------------------------------
         < Continue , Skip or Quit > :
*C
         Time          Cumulative Energy
         -------------------------------

         0.00000             0.01238
         0.10000             0.09342
         0.20000             0.24087
         0.30000             0.44705
         0.40000             0.71132
         0.50000             1.03025
         0.60000             1.38893
         0.70000             1.77981
         0.80000             2.28804
         0.90000             3.14488
         1.00000             4.60680
         1.09999             6.62840
         1.19999             9.05036
         < Continue , Skip or Quit > :
*C

         1.29999            11.97972
         1.39999            15.31400
         1.49999            18.33119
         1.59999            20.93636
         1.69999            23.33017
         1.79999            24.56225
```

```
        1.89999              25.22356
        1.99999              25.30659
        2.09999              25.39939
        2.19999              26.44630
        2.29999              27.26550
        2.39999              28.01795
        2.49999              28.69922
        2.59999              29.40439
        2.69999              30.62130
        2.79999              32.32354
        2.89999              34.17930
        2.99999              36.03450
        3.09999              38.70782
        < Continue , Skip or Quit > :
*C
        3.19999              41.40761
        3.29999              43.83021
        3.39999              46.24371
        3.49999              47.90289
        3.59999              48.69909
        3.69999              49.17960
        3.79999              49.33037
        3.89999              49.40648
        3.99999              49.46260
        4.09999              50.17543
        4.19999              51.42637
        4.29999              53.03884
        4.39999              55.26048
        4.49999              58.27361
        4.59999              62.25598
        4.69999              67.39534
        4.80000              74.56405
        4.90000              84.26932
        5.00000              95.57339
        < Continue , Skip or Quit > :
*C

*PDS    /

        < Continue , Skip or Quit > :
*C

          Time history of the internal coordinates of the joints
        ----------------------------------------------------------

        Time          Joint 1       Joint 2       Joint 3       Joint 4

        0.00000       0.52809       1.04219      -0.43632       0.17453
        0.10000       0.54184       1.02659      -0.43632       0.17453
        0.20000       0.56509       0.99969      -0.43632       0.17453
        0.30000       0.59799       0.96139      -0.43632       0.17453
        0.40000       0.64089       0.91154      -0.43632       0.17453
        0.50000       0.69399       0.84999      -0.43632       0.17453
        0.60000       0.75729       0.77674      -0.43632       0.17453
```

```
      0.70000        0.83194       0.69174      -0.43632       0.17453
      0.80000        0.91934       0.59359      -0.43632       0.17453
      0.90000        1.01974       0.48069      -0.43027       0.17453
      1.00000        1.13339       0.35274      -0.41202       0.17453
      1.09999        1.25839       0.21149      -0.38147       0.17866
      1.19999        1.39259       0.06099      -0.33922       0.19113
      1.29999        1.53559      -0.09650      -0.28592       0.21198
      < Continue , Skip or Quit > :
*C

      1.39999        1.68479      -0.25975      -0.22252       0.24133
      1.49999        1.83911      -0.42695      -0.14997       0.28123
      1.59999        1.99581      -0.59750      -0.06862       0.33393
      1.69999        2.15374      -0.77135       0.02107       0.39963
      1.79999        2.31164      -0.94735       0.11862       0.47843
      1.89999        2.46954      -1.12335       0.22392       0.56948
      1.99999        2.62744      -1.29930       0.33742       0.67123
      2.09999        2.78159      -1.45590       0.45512       0.78278
      2.19999        2.92839      -1.60840       0.57282       0.90333
      2.29999        3.05534      -1.75390       0.69052       1.03278
      2.39999        3.18979      -1.89400       0.80822       1.17138
      2.49999        3.30174      -2.02870       0.92592       1.31908
      2.59999        3.40154      -2.15535       1.04102       1.47138
      2.69999        3.48934      -2.27130       1.15027       1.62368
      2.79999        3.56394      -2.37535       1.25302       1.77598
      2.89999        3.62434      -2.46630       1.34927       1.92828
      2.99999        3.66939      -2.54160       1.43902       2.08058
      3.09999        3.69794      -2.59870       1.51877       2.22968
      3.19999        3.71314      -2.63720       1.58502       2.37238
      < Continue , Skip or Quit > :
*C

      3.29999        3.71814      -2.65670       1.63777       2.50883
      3.39999        3.71304      -2.65720       1.67752       2.63913
      3.49999        3.70034      -2.64270       1.70877       2.76358
      3.59999        3.68244      -2.61720       1.73552       2.88253
      3.69999        3.66194      -2.58070       1.75852       2.99598
      3.79999        3.64144      -2.53465       1.77852       3.10668
      3.89999        3.62094      -2.48050       1.79552       3.22098
      3.99999        3.60044      -2.41920       1.81027       3.34248
      4.09999        3.58569      -2.35225       1.82352       3.47073
      4.19999        3.58244      -2.28025       1.83527       3.60538
      4.29999        3.59144      -2.20325       1.84627       3.74328
      4.39999        3.61394      -2.12125       1.85727       3.88118
      4.49999        3.65049      -2.03450       1.87137       4.01908
      4.59999        3.70134      -1.94350       1.89172       4.15698
      4.69999        3.76689      -1.84850       1.91812       4.29488
      4.80000        3.84849      -1.74975       1.94992       4.43218
      4.90000        3.94729      -1.64750       1.98672       4.56338
      5.00000        4.06219      -1.54350       2.02852       4.68358
      /
*C

      / Illegal command
      /
*EXIT
```

```
           >>
*PLOT

           * Please go to the Graphics room
           >>
*ED

           %
*HELP

           The following is a summary of commands
           --------------------------------------------
           HELP             : type this text
           SYSTEM           : change the system of units,coordinates
           etc.
           CONFIG           : change the manipulator configuration
           STATE            : change the manipulator state
           TASK             : change the manipulator task
           EXIT             : end edit
           %
*CONFIG

           * Add,delete or change :
*CHANGE

           * linkno    :
*1

           * Configuration parameter :
*LINKT

           * Configuration parameter :Ambiguous command
           * Configuration parameter :
*LINKTWIST

           * value    :
*75.0

           * Configuration parameter :
*EXIT

           * Add,delete or change :
*CHA

           * linkno    :
*3

           * Configuration parameter :
*LINKTW

           * value    :
*75.0

           * Configuration parameter :
*EX
```

```
          * Add,delete or change :
*CH
          * linkno    :
*4
          * Configuration parameter :
*RHO

          * value    :    *
          * value : Rho(1) :
*-0.00095

          *
          * value : Rho(2) :
*0.025

          *
          * value : Rho(3) :
*0.00205

          * Configuration parameter :
*EXIT
          * Add,delete or change :
*EXIT
          %
*CONFIG
          * Add,delete or change :
*C
          * linkno    :
*4
          * Configuration parameter :
*MASS
          * value    :
*16.5
          * Configuration parameter :
*EXIT
          * Add,delete or change :
*EXIT
          %
*EXIT
          >>
*TYPE INP
          !
```

```
*CON

         This manipulator is an open chain active mechanism with 4 degrees
         of freedom
         < Continue , Skip or Quit > :
*C

         Link  1
         ---------
         LINKTYPE          :  Revolute
         LINKLENGTH        :     0.00000
         LINKTWIST         :    75.00000
         JOINTDIST         :     0.76500
         JOINTANGLE        :  Variable
         RHO               :     0.00000
                                -0.67499
                                 0.01499
         MASS              :    95.99000
         INERTIA           :    33.72399      0.00000      0.00000
                                 0.00000      2.87900      0.60900
                                 0.00000      0.60900     33.05600
         REDUCT. RATIO     :   100.00000
         EFFICIENCY        :     0.85000
         < Continue , Skip or Quit > :
*C

         Link  2
         ---------
         LINKTYPE          :  Revolute
         LINKLENGTH        :     0.00000
         LINKTWIST         :   -90.00000
         JOINTDIST         :     0.00000
         JOINTANGLE        :  Variable
         RHO               :     0.00000
                                 0.01000
                                -0.20300
         MASS              :    82.60999
         INERTIA           :     3.99000      0.00000      0.00099
                                 0.00000      3.78599     -1.53999
                                 0.00099     -1.53999      1.47499
         REDUCT. RATIO     :   100.00000
         EFFICIENCY        :     0.85000
         < Continue , Skip or Quit > :
*C

         Link  3
         ---------
         LINKTYPE          :  Revolute
         LINKLENGTH        :    -0.03500
         LINKTWIST         :    75.00000
         JOINTDIST         :     0.51000
         JOINTANGLE        :  Variable
         RHO               :     0.02900
                                -0.52400
                                -0.00700
```

```
         MASS                :    52.90000
         INERTIA             :     3.29500       0.17799      -0.01200
                                   0.17799       0.42500       0.19500
                                  -0.01200       0.19500       3.23693
         REDUCT. RATIO       :   100.00000
         EFFICIENCY          :     0.85000
         < Continue , Skip or Quit > :
*C

         Link  4
         ---------
         LINKTYPE            : Revolute
         LINKLENGTH          :     0.00000
         LINKTWIST           :   -90.00000
         JOINTDIST           :     0.00000
         JOINTANGLE          : Variable
         RAD                 :     0.00095
                                   0.02500
                                   0.00205
         MASS                :    16.50000
         INERTIA             :     0.15000       0.00000      -0.00099
                                   0.00000       0.05199       0.00099
                                  -0.00099       0.00099       0.15000
         REDUCT. RATIO       :   109.99999
         EFFICIENCY          :     0.85000
         < Continue , Skip or Quit > :
*C

         | EXIT
*SIMULATE

         >> Simulation going on. Please wait.
         ENERGY CONSUMED =    121.06260
         >>

*TYPE OUT
         /
*DR
         < Continue , Skip or Quit > :
*C
```

Time history of the DRIVES in the joints

Time	Joint1	Joint2	Joint3	Joint4
0.00000	13.74070	6.86060	11.78751	9.01055
0.10000	14.61155	6.78617	12.43711	10.39404
0.20000	14.94331	6.96051	13.12725	11.42567
0.30000	15.00524	7.96021	14.89157	13.28165
0.40000	17.55056	9.21791	17.30693	16.08421
0.50000	18.74850	10.40795	19.68270	18.97062
0.60000	23.27353	11.94359	22.45527	22.31926
0.70000	27.12037	18.31072	30.25411	29.17317
0.80000	31.01602	20.47518	34.35925	35.83124
0.90000	34.25520	23.41013	41.16369	42.32123
1.00000	39.23971	28.03960	44.63923	45.72986

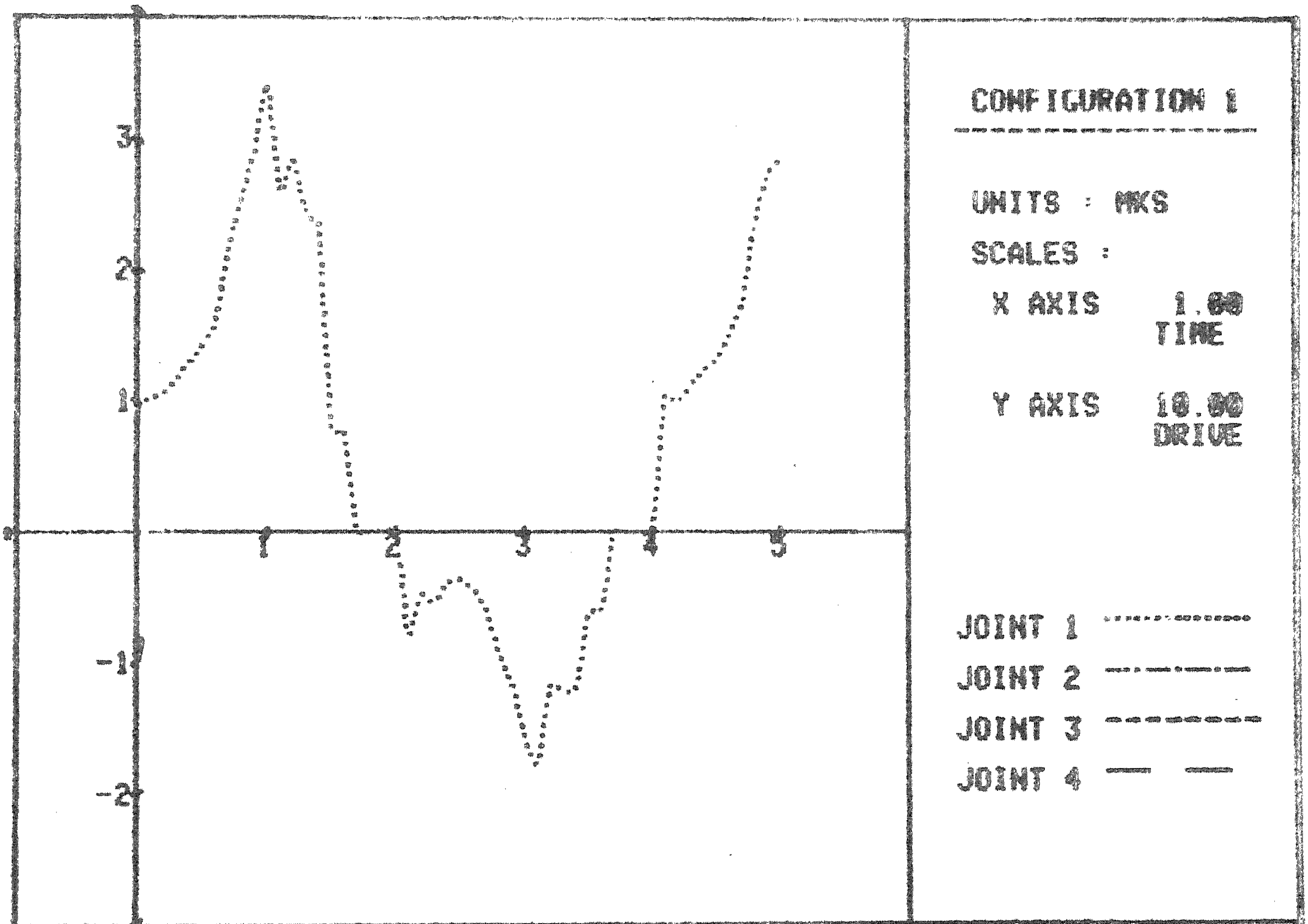
```
          1.09999     29.27642     20.75691     33.80249     35.18084
          1.19999     31.55895     24.83170     35.46454     32.54878
          < Continue , Skip or Quit > :
*C
          1.29999     25.75618     19.90562     29.51930     26.92664
          1.39999     25.94739     20.29283     30.64755     25.05974
          1.49999      8.15862      4.75859     13.82935      9.40936
          1.59999      3.44115      5.39502     15.22059      9.48382
          1.69999      0.00000     -1.41716      3.35324     -1.62262
          1.79999      0.00000      2.10216     -2.18844     -9.47385
          1.89999      0.00000      5.36024    -10.15875    -19.26290
          1.99999      0.00000     11.80573    -17.95385    -33.38384
          2.09999    -11.07157      1.29270    -44.19419    -54.01735
          2.19999     -3.77884      3.11530    -40.81881    -47.85647
          2.29999    -12.10318     -2.21180    -41.10342    -41.07900
          2.39999    -11.00845     -1.88985    -34.50279    -32.45561
          2.49999    -10.88441     -2.64212    -28.95513    -25.53740
          2.59999    -11.05545     -0.21461    -27.25918    -27.30132
          2.69999    -12.84924     -2.11287    -24.26042    -24.07183
          2.79999    -15.99039     -4.02481    -20.72690    -22.72671
          2.89999    -19.09877     -6.06151    -17.57055    -20.54141
          2.99999    -24.43332     -6.98184    -14.60845    -22.94565
          3.09999    -25.23392     -8.65044    -18.95872    -28.02934
          < Continue , Skip or Quit > :
*C
          3.19999    -15.95342     -1.27478    -13.87507    -24.60248
          3.29999    -17.35402     -1.65030    -13.47501    -24.87649
          3.39999    -17.14415     -1.51727    -12.32801    -24.22572
          3.49999     -8.84579     -0.42354     -4.96890    -10.65112
          3.59999     -8.67497     -0.27490     -4.99085    -10.62833
          3.69999      0.00000      6.24599     -1.61713     -6.79545
          3.79999      0.00000      4.31932     -2.27541     -4.81206
          3.89999      0.00000      4.28553     -2.13189     -4.43416
          3.99999      0.00000      2.98343     -1.12463     -1.83719
          4.09999     15.39363     14.33736      2.06039      3.14982
          4.19999     15.01261     13.97583      3.02046      4.01671
          4.29999     18.00766     15.61871      5.68716      6.26371
          4.39999     19.67315     17.23994      7.75534      7.94189
          4.49999     20.53692     18.13171     12.38553     11.78267
          4.59999     22.37938     20.04864     14.62174     13.61500
          4.69999     24.89546     23.17763     17.56763     15.56604
          4.80000     31.72333     30.03334     24.03828     21.10753
          4.90000     35.61730     35.12112     29.75720     25.04080
          5.00000     35.28149     33.72117     30.95708     27.54543
          < Continue , Skip or Quit > :
*C
          /
*PN
          < Continue , Skip or Quit > :
*C
          The PN diagram
          --------------

          JOINT 1
          -------
```

```
RPM             TORQUE

85.94099         0.11579
176.55549         0.12419
267.37199         0.12701
360.95219         0.13604
453.35203         0.14917
555.75150         0.15936
653.15158         0.17232
772.51459         0.23052
896.55110         0.25363
1020.78810         0.29116
1119.54959         0.33353
< Continue , Skip or Quit > :
*C
1237.55210         0.24885
1325.40121         0.26825
1395.05330         0.22742
1452.90640         0.22055
1489.85950         0.07189
1507.78713         0.07175
1507.78713         0.00000
1507.78713         0.00000
1507.78713         0.00000
1507.78713         0.00000
1436.16962        -0.09920
1367.41632        -0.07462
1248.05434        -0.10542
1128.69183        -0.09357
1009.32933        -0.09251
896.55113        -0.09397
780.15333        -0.10921
644.55753        -0.14441
508.95173        -0.16233
< Continue , Skip or Quit > :
*C
351.40324        -0.20768
193.84474        -0.22298
96.44494        -0.14410
-0.95485        -0.14750
-96.44485        -0.14572
-146.09965        -0.07518
-195.75445        -0.07373
-195.75445         0.00000
-195.75445         0.00000
-195.75445         0.00000
-195.75445         0.00000
-85.94095         0.13934
23.87254         0.13610
148.00954         0.15306
281.69554         0.16722
416.33644         0.17456
554.79593         0.19022
697.07702         0.21161
861.31982         0.26964
< Continue , Skip or Quit > :
```

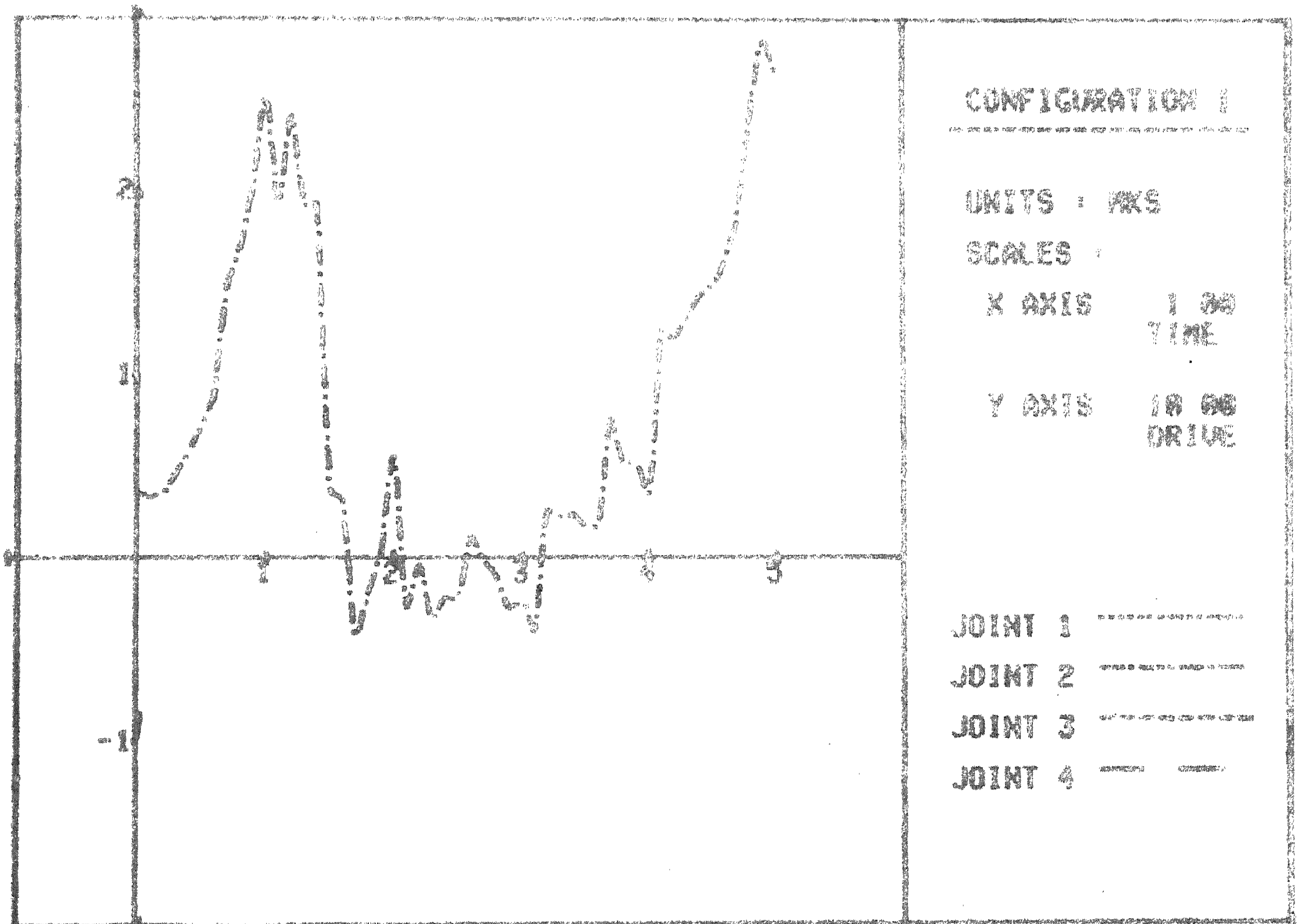
```
*C
        1023.33264          0.30274
        1163.77764          0.29989
        < Continue , Skip or Quit > :
*Q
          /
*EN
        < Continue , Skip or Quit > :
*C
        Time history of the ENERGY consumption
        --------------------------------------

        Time            Cumulative Energy

        0.00000             0.01376
        0.10000             0.10224
        0.20000             0.26092
        0.30000             0.48429
        0.40000             0.77590
        0.50000             1.13565
        0.60000             1.55207
        0.70000             2.03524
        0.80000             2.67239
        0.90000             3.70013
        1.00000             5.36794
        1.09999             7.57005
        < Continue , Skip or Quit > :
*C
        1.19999            10.10647
        1.29999            13.09022
        1.39999            16.42408
        1.49999            19.28614
        1.59999            21.42387
        1.69999            22.83583
        1.79999            23.15594
        1.89999            24.45757
        1.99999            27.00784
        2.09999            28.38400
        2.19999            30.68638
        2.29999            33.00632
        2.39999            35.39698
        2.49999            37.47598
        2.59999            39.54023
        2.69999            41.82240
        2.79999            44.50722
        2.89999            47.50759
        2.99999            50.79153
        < Continue , Skip or Quit > :
*
*C
        3.09999            54.42280
        3.19999            57.60974
        3.29999            60.37838
        3.39999            63.15331
        3.49999            65.20423
        3.59999            66.45513




        3.69999            67.32159
        3.79999            67.75973
        3.89999            68.09264
        3.99999            68.27485
        4.09999            69.06593
        4.19999            70.65021
        4.29999            72.69942
        4.39999            75.52394
        4.49999            79.29503
        4.59999            84.14935
        4.69999            90.18897
        4.80000            98.30549
        4.90000           108.98030
        < Continue , Skip or Quit > :
*C
        5.00000           121.06260
        /
*HELP
        The commands are
        ----------------
        HELP            : type this text
        DRIVE           : display drives in joints
        POSITION        : display joint positions
        VELOCITY        : display joint velocity
```

```
                PW DIAG          : Display Torque - Rom diagram
                ENERGY           : display energy consumption for task
                EXIT             : end output parameters display
                /
*EX
                >>
*DOC
                * Chapter :
*INTRO
                Dynamic performance is one of the most significant
                actors in designing mechanical arms particularly for fast
                nd accurate robots recently developed.
                Until now the choice of the kinematic scheme and its
                ifferent parameters , actuator and the control systems
                nits was a subject of free speculation,frequently based on
                xperience but lacking any systematic method.Hence the need
                or developing certain criteria and procedures for a
                ystematic choce of manipulator design.In the design
                hase,there is no efficient means except simulation to
                nvestigate and evaluate the highly non linear and coupled
                ystems. The aim of my work was to create a software tool
                or the simulation of all the dynamical values and
                haracteristics of manipulator operations in a particular
                ask execution and thus permit a fast evaluation of a great
                umber of different configurations.
                < Continue , Skip or Quit > :
*QUIT
                * Chapter :
*EXIT
```

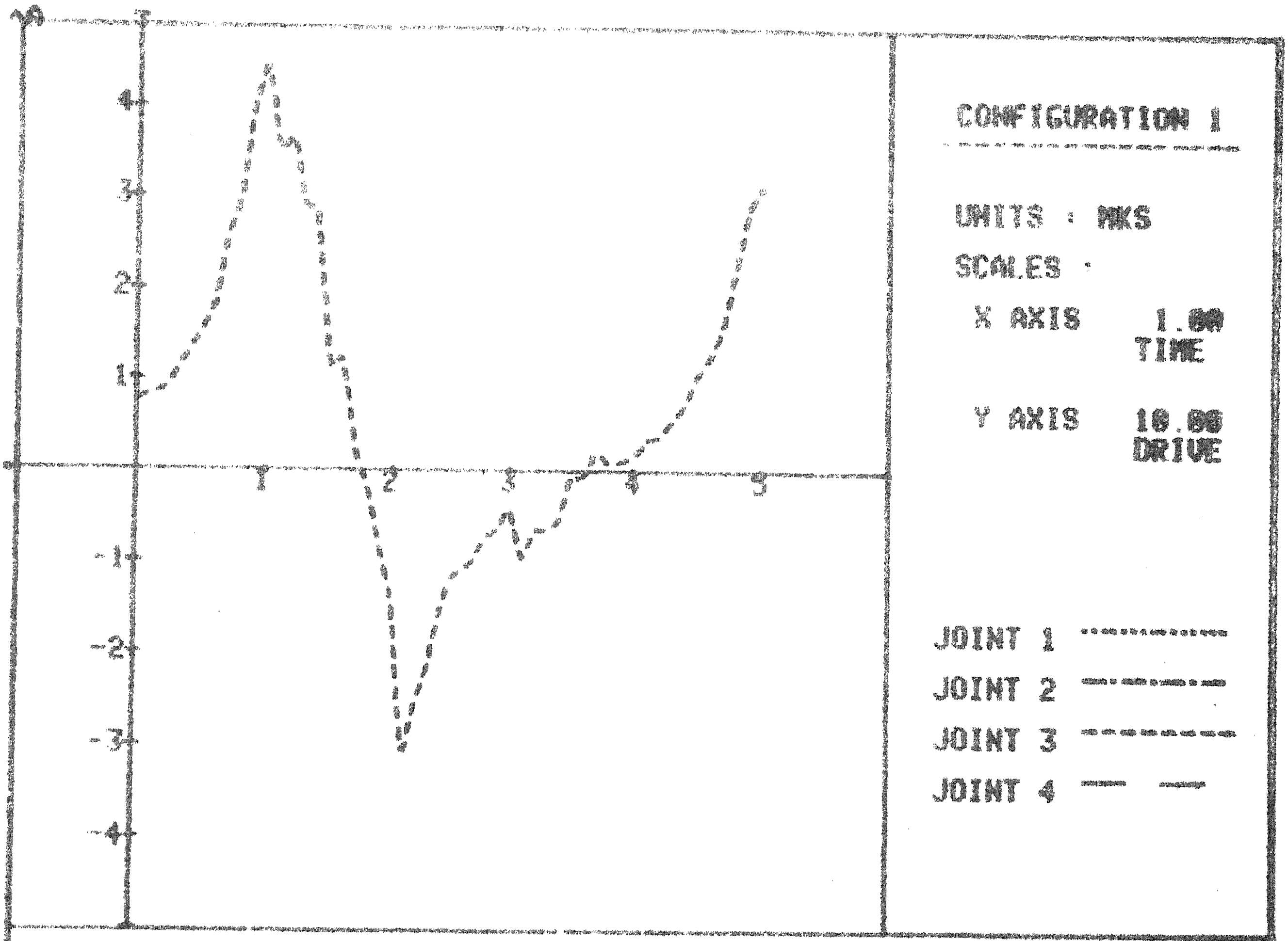
```
*EXIT
```



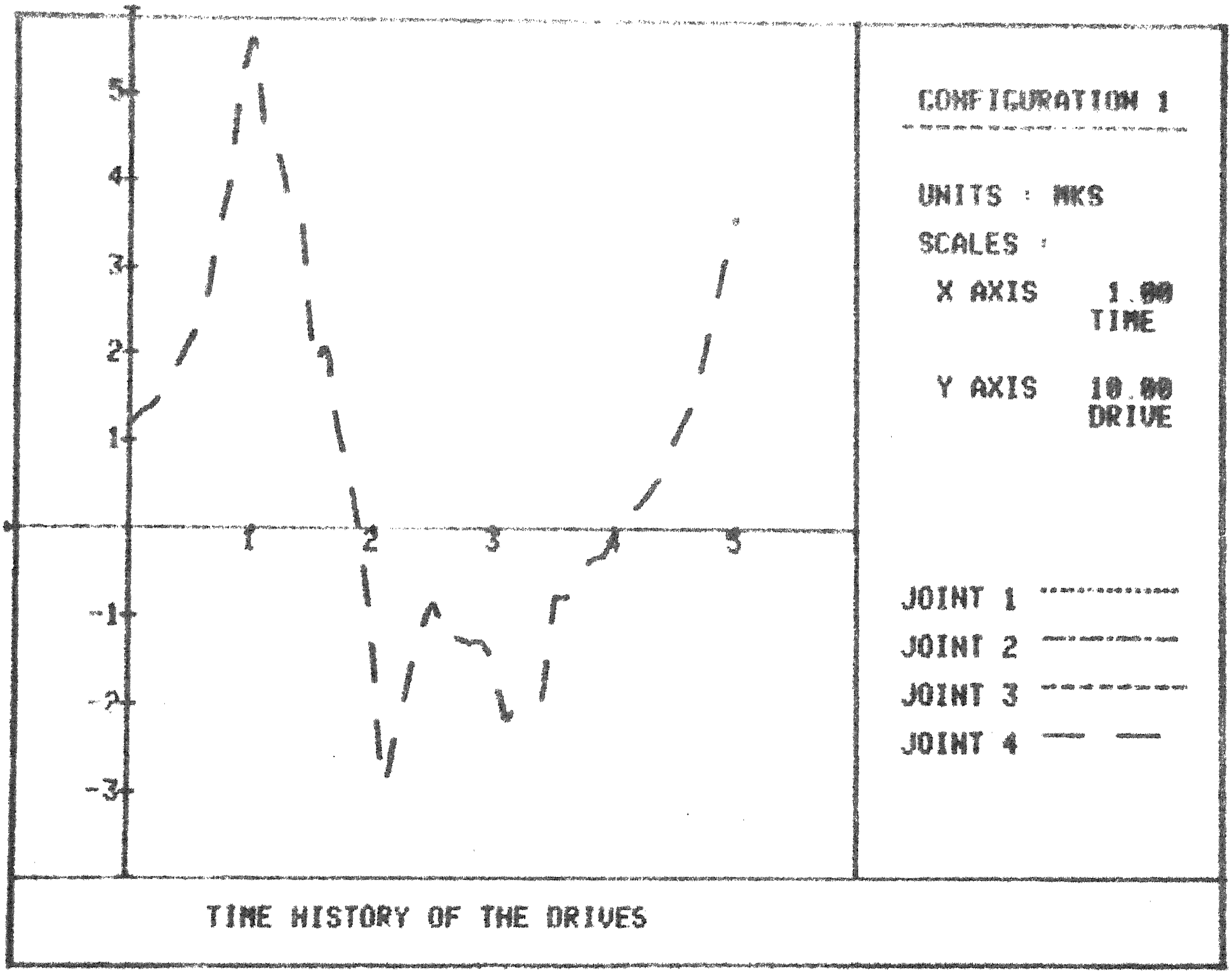
TIME HISTORY OF THE DRIVES

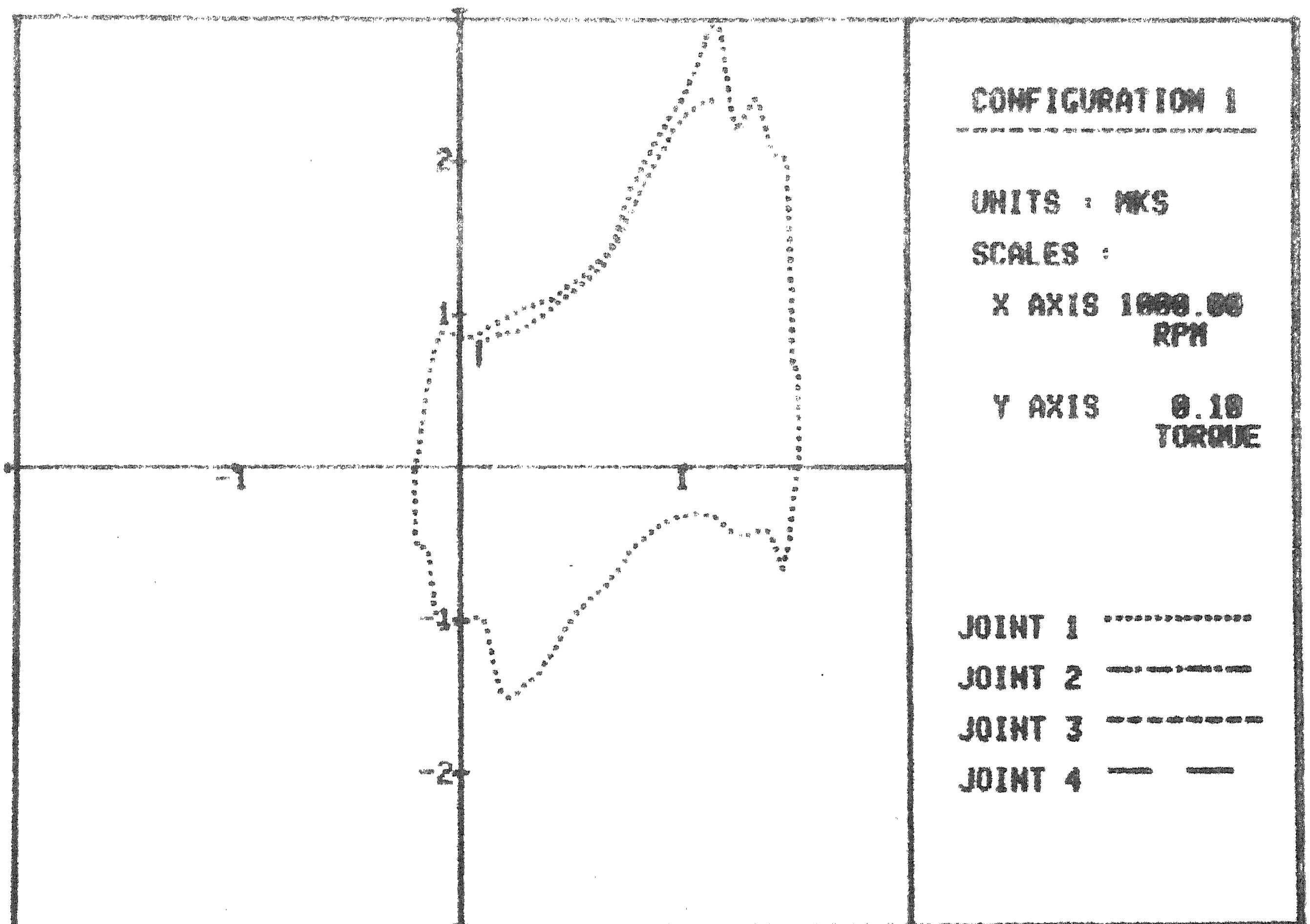


TIME HISTORY OF THE DRIVES

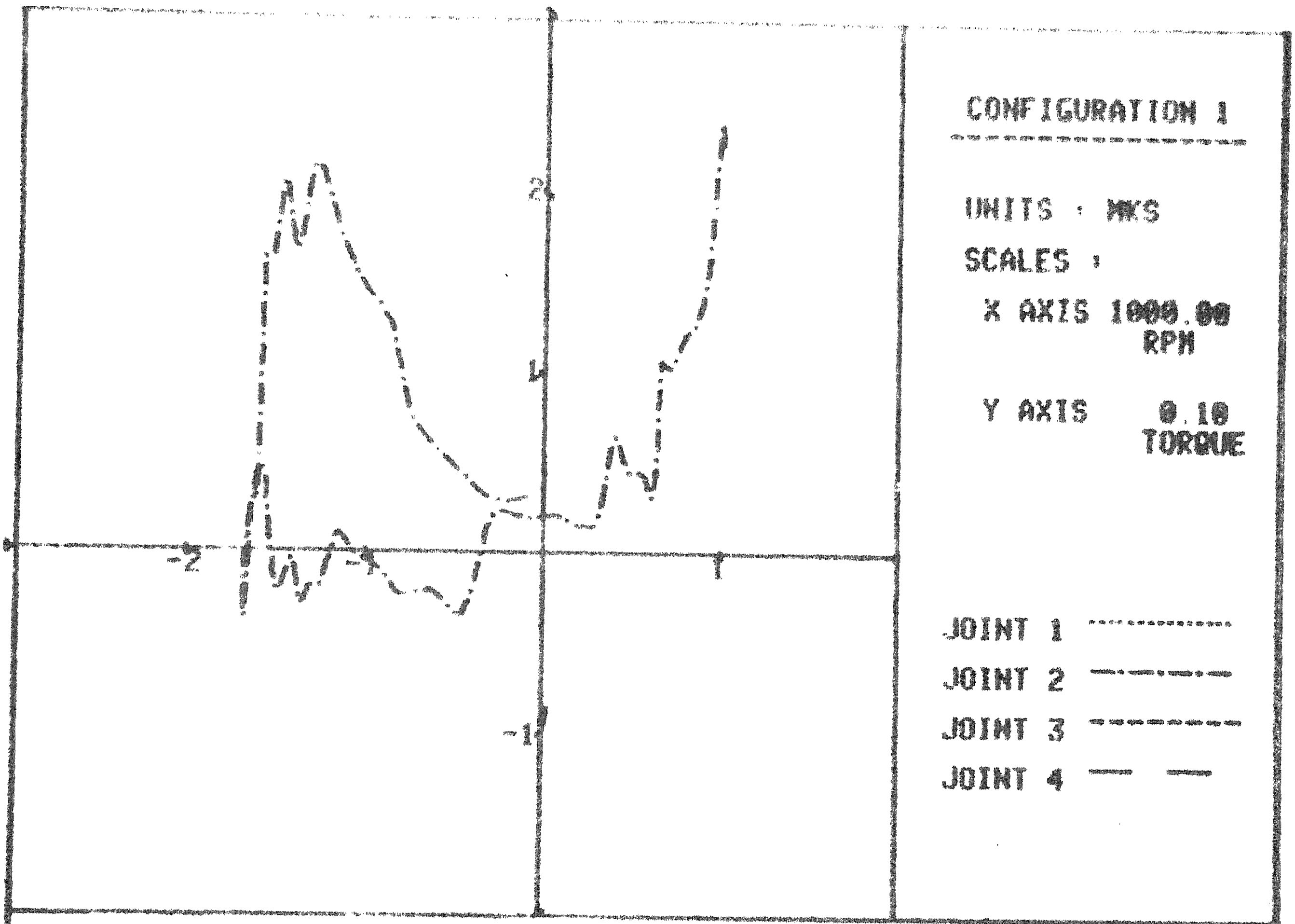


TIME HISTORY OF THE DRIVES

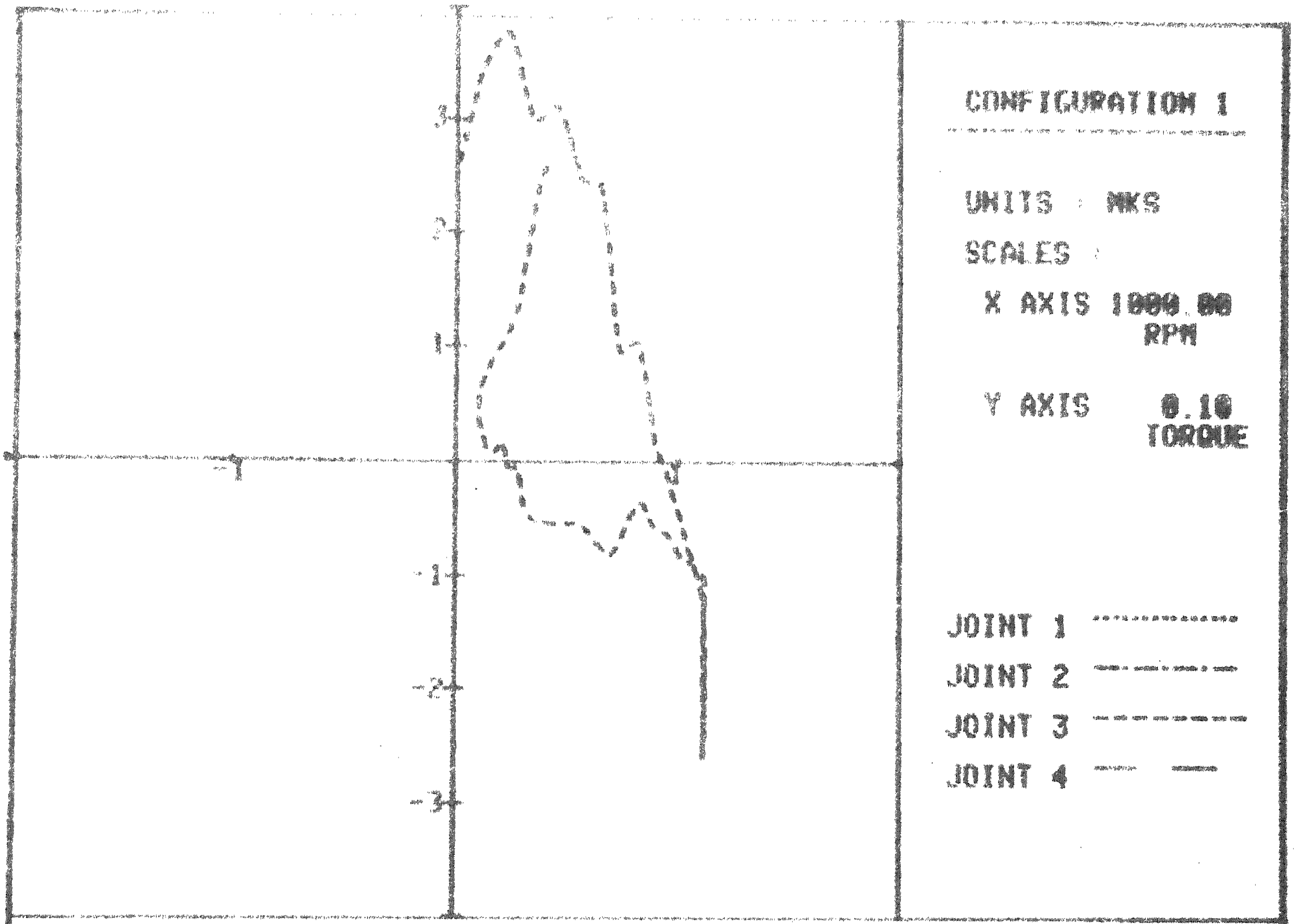

5
4
3
2
1
-1
-2
-3
1
2
3
4
5
CONFIGURATION 1
UNITS : MKS
SCALES :
X AXIS 1.00
TIME
Y AXIS 10.00
DRIVE
JOINT 1
JOINT 2
JOINT 3
JOINT 4
TIME HISTORY OF THE DRIVES



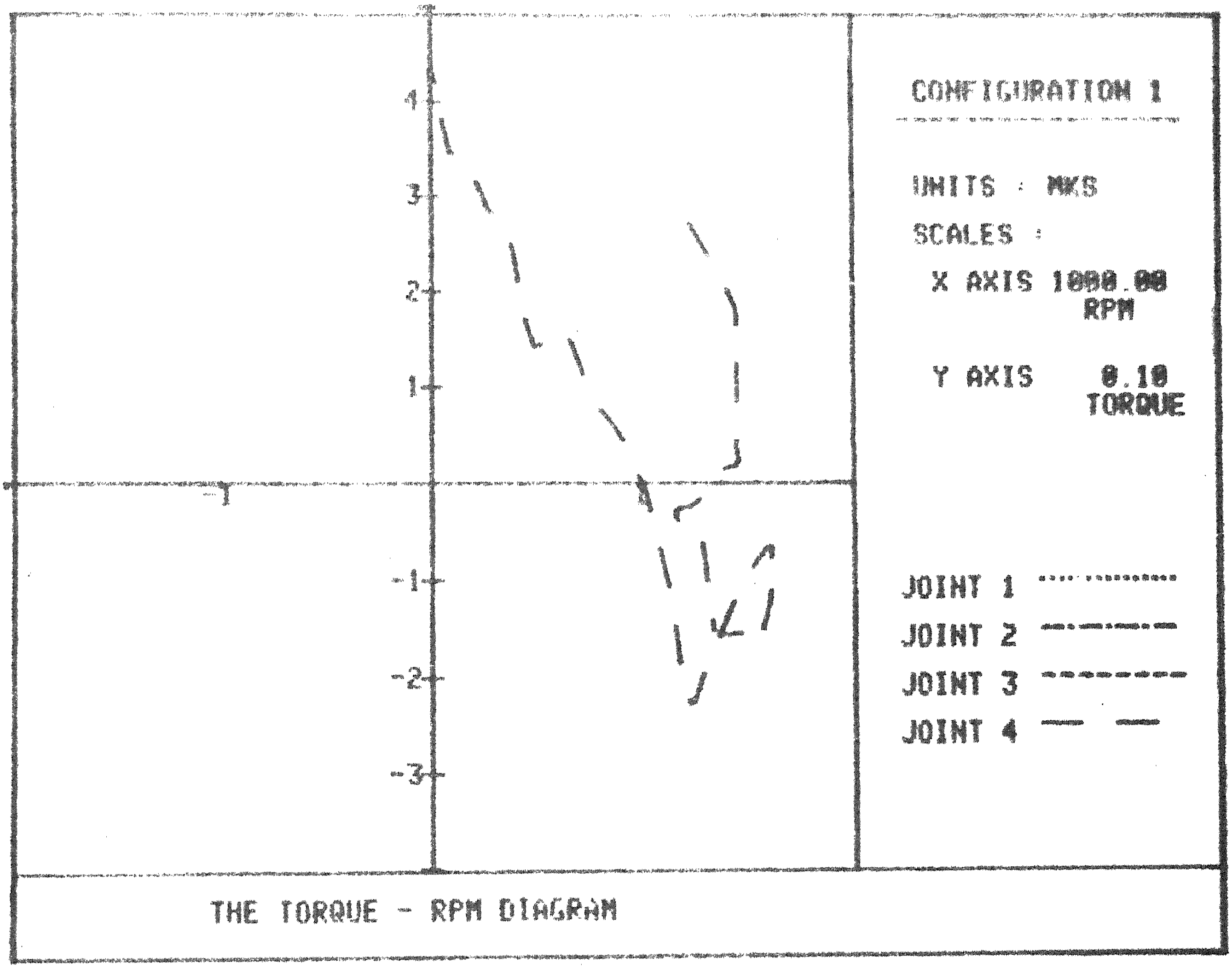
THE TORQUE - RPM DIAGRAM

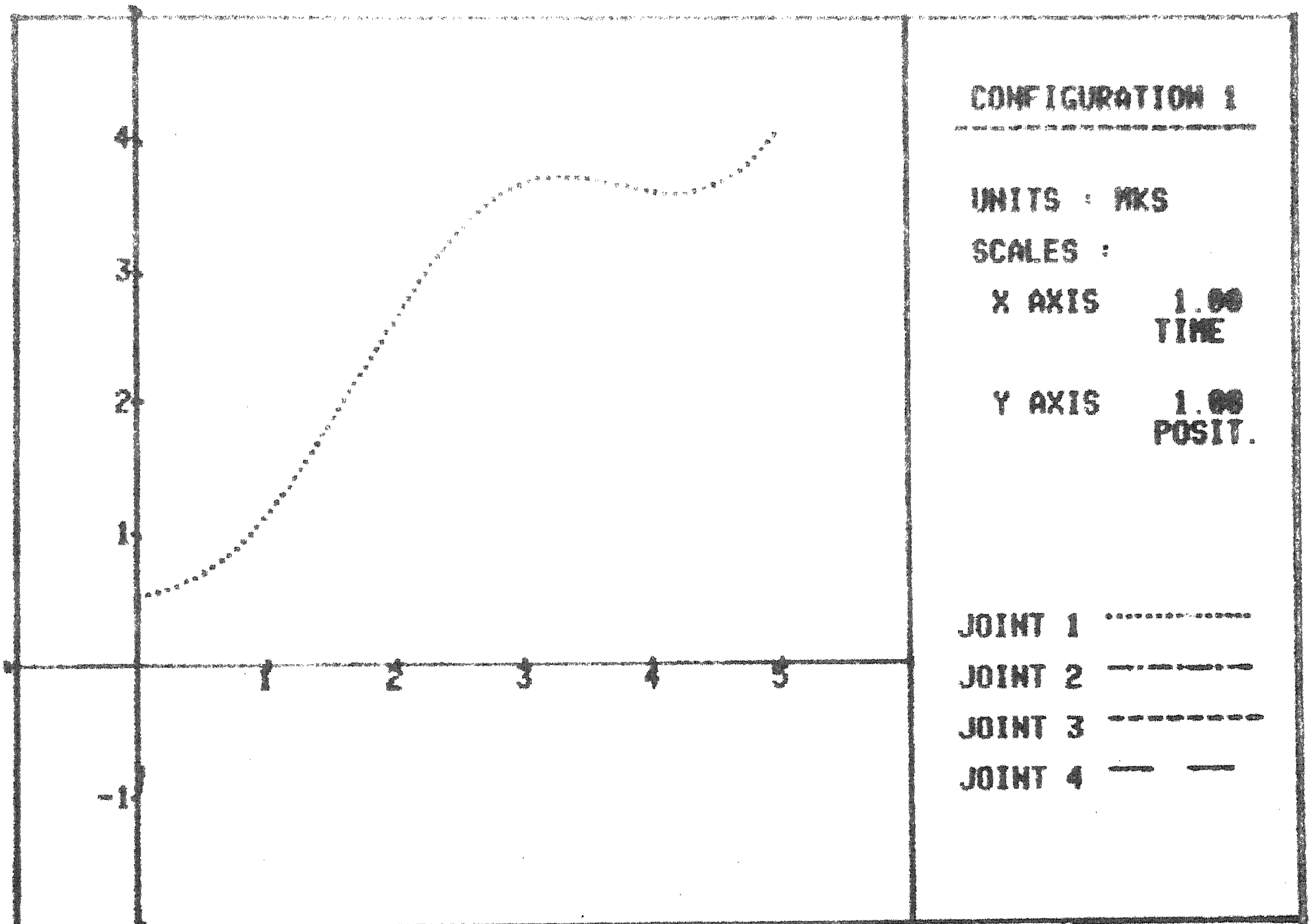


THE TORQUE - RPM DIAGRAM

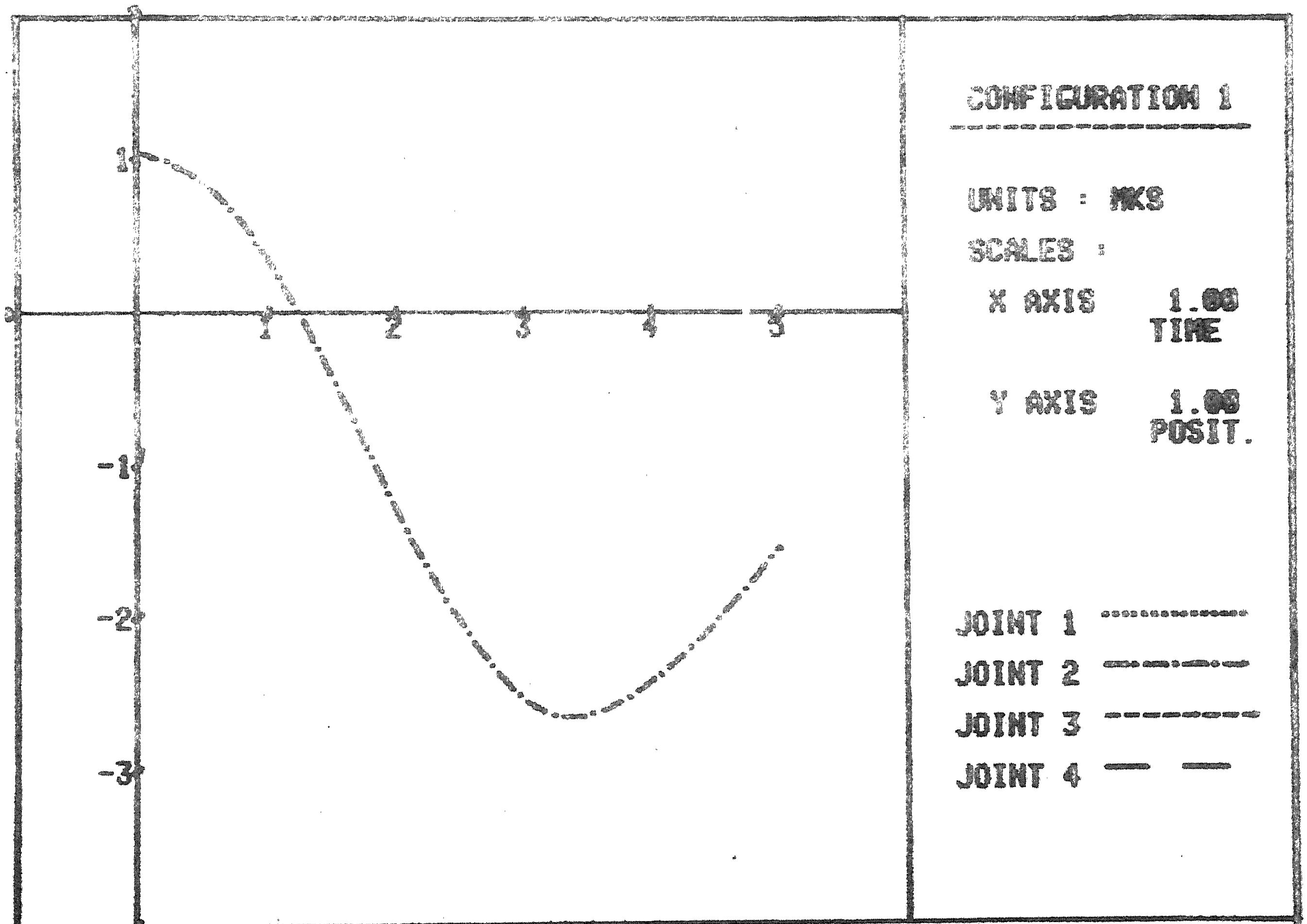


THE TORQUE - RPM DIAGRAM

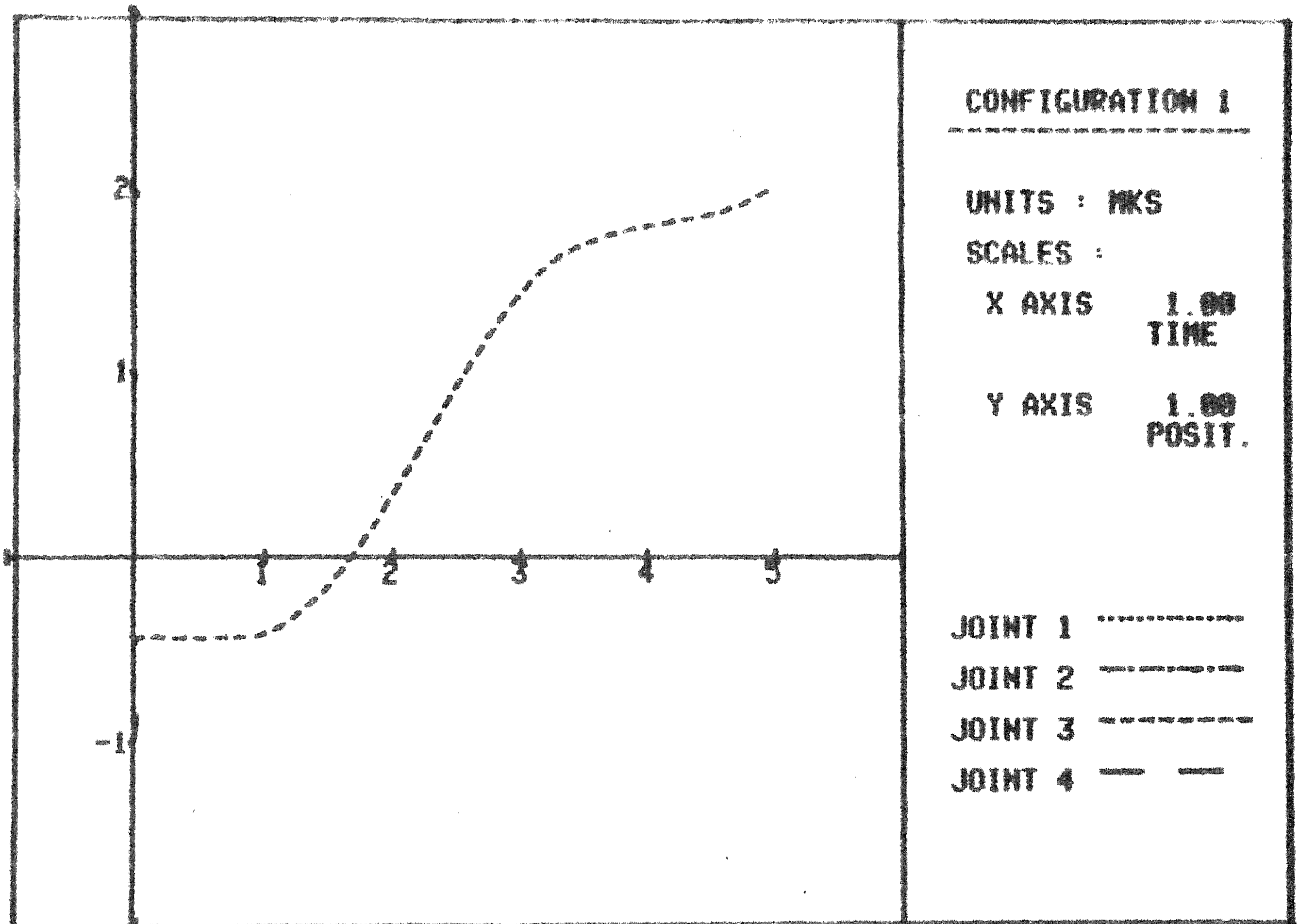

4
3
2
1
-1
-2
-3
CONFIGURATION 1
UNITS : MKS
SCALES :
X AXIS 1000.00
RPM
Y AXIS 0.10
TORQUE
JOINT 1
JOINT 2
JOINT 3
JOINT 4
THE TORQUE - RPM DIAGRAM



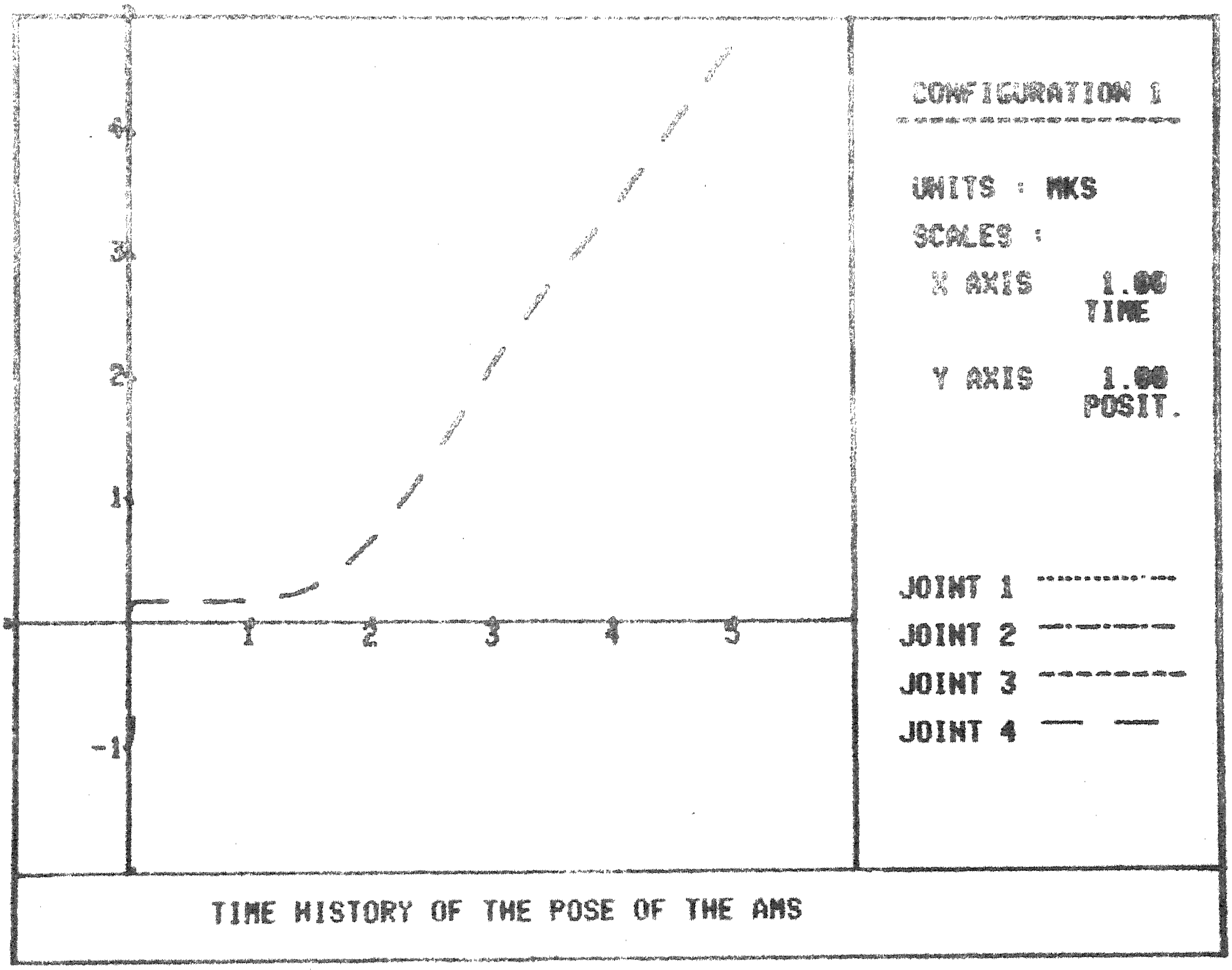
TIME HISTORY OF THE POSE OF THE AMS

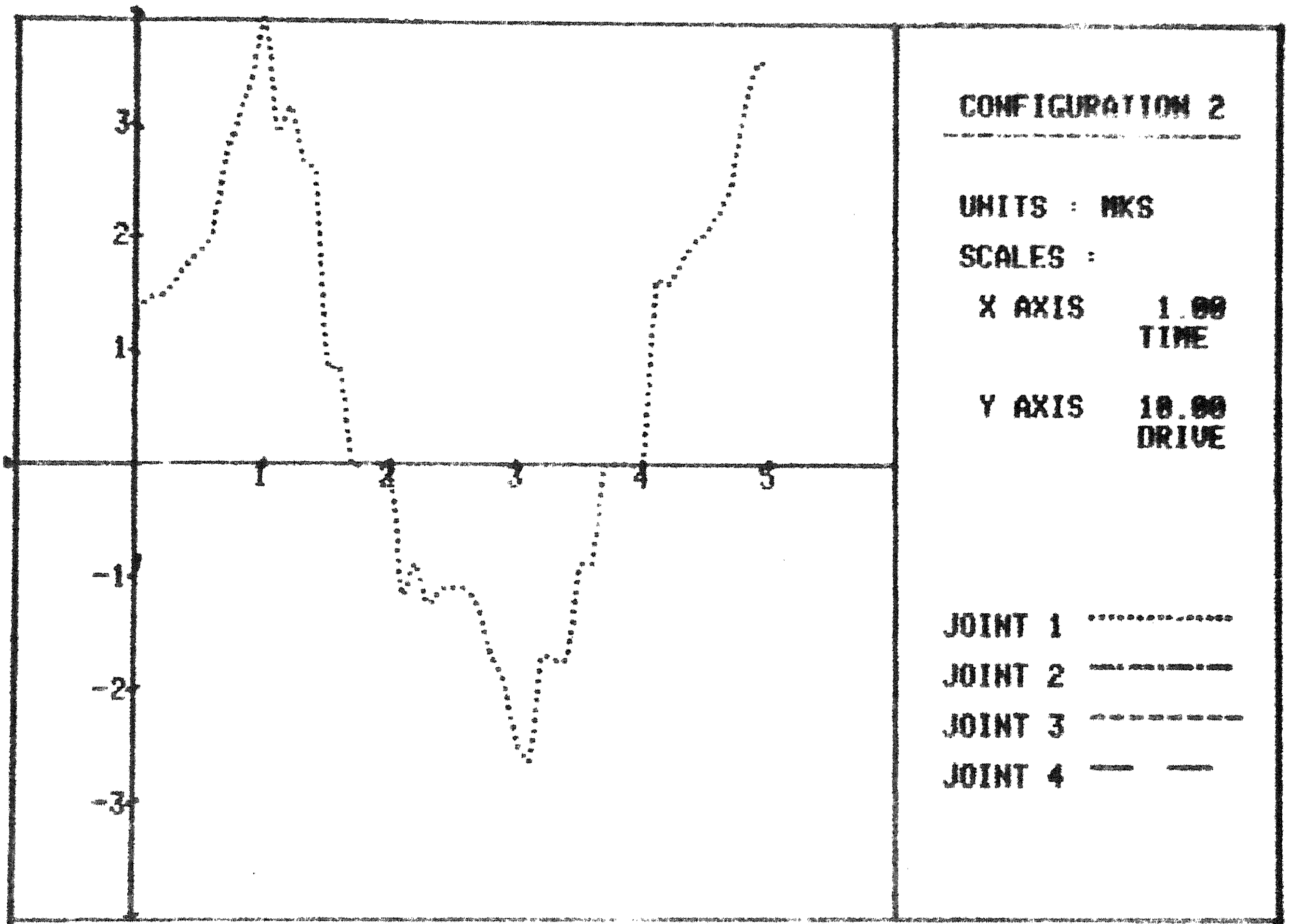


TIME HISTORY OF THE POSE OF THE AMS

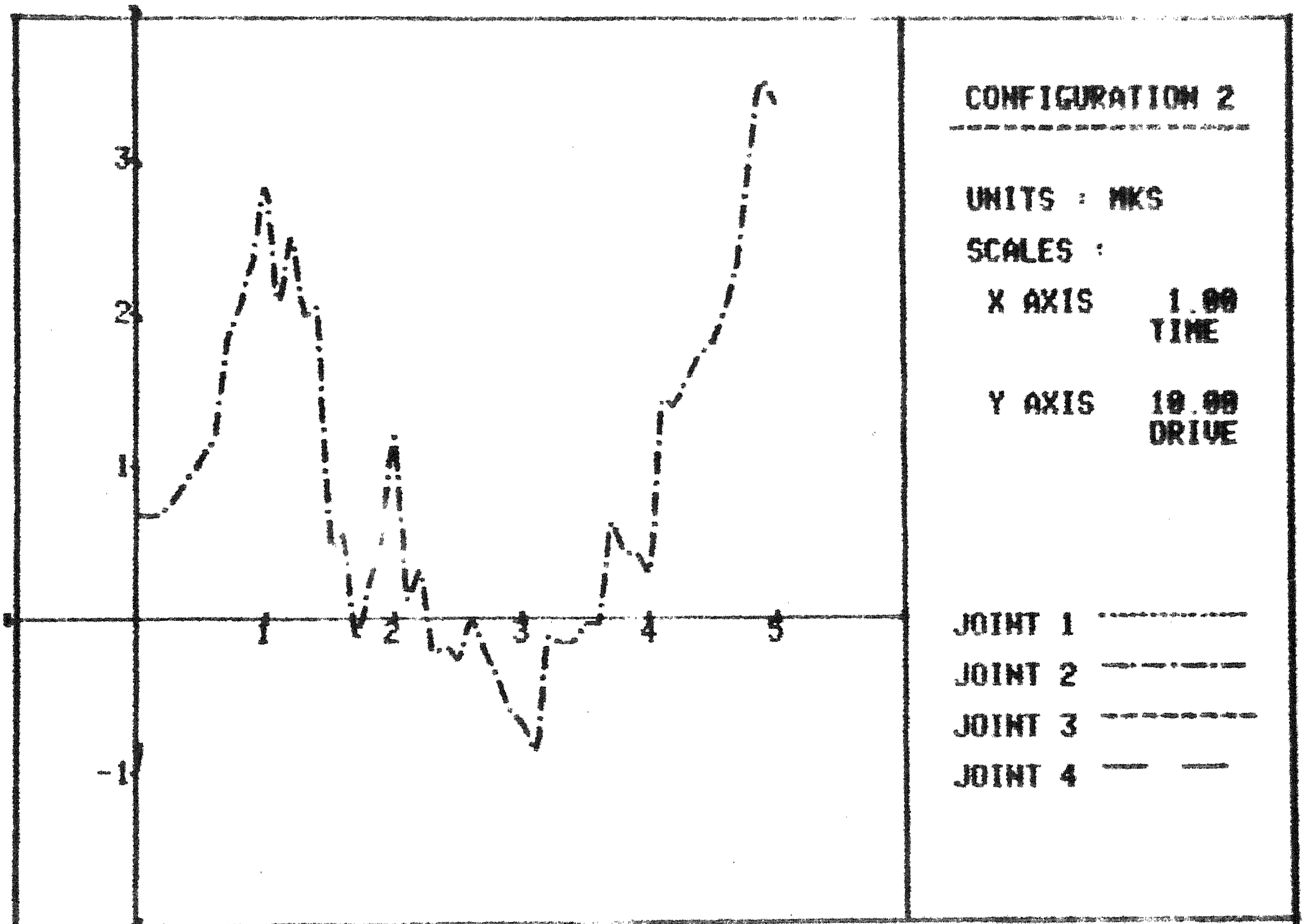


TIME HISTORY OF THE POSE OF THE AMS


CONFIGURATION 1
UNITS : MKS
SCALES :
X AXIS 1.00 TIME
Y AXIS 1.00 POSIT.
JOINT 1
JOINT 2
JOINT 3
JOINT 4
1
2
3
4
5
-1
TIME HISTORY OF THE POSE OF THE AMS



TIME HISTORY OF THE DRIVES



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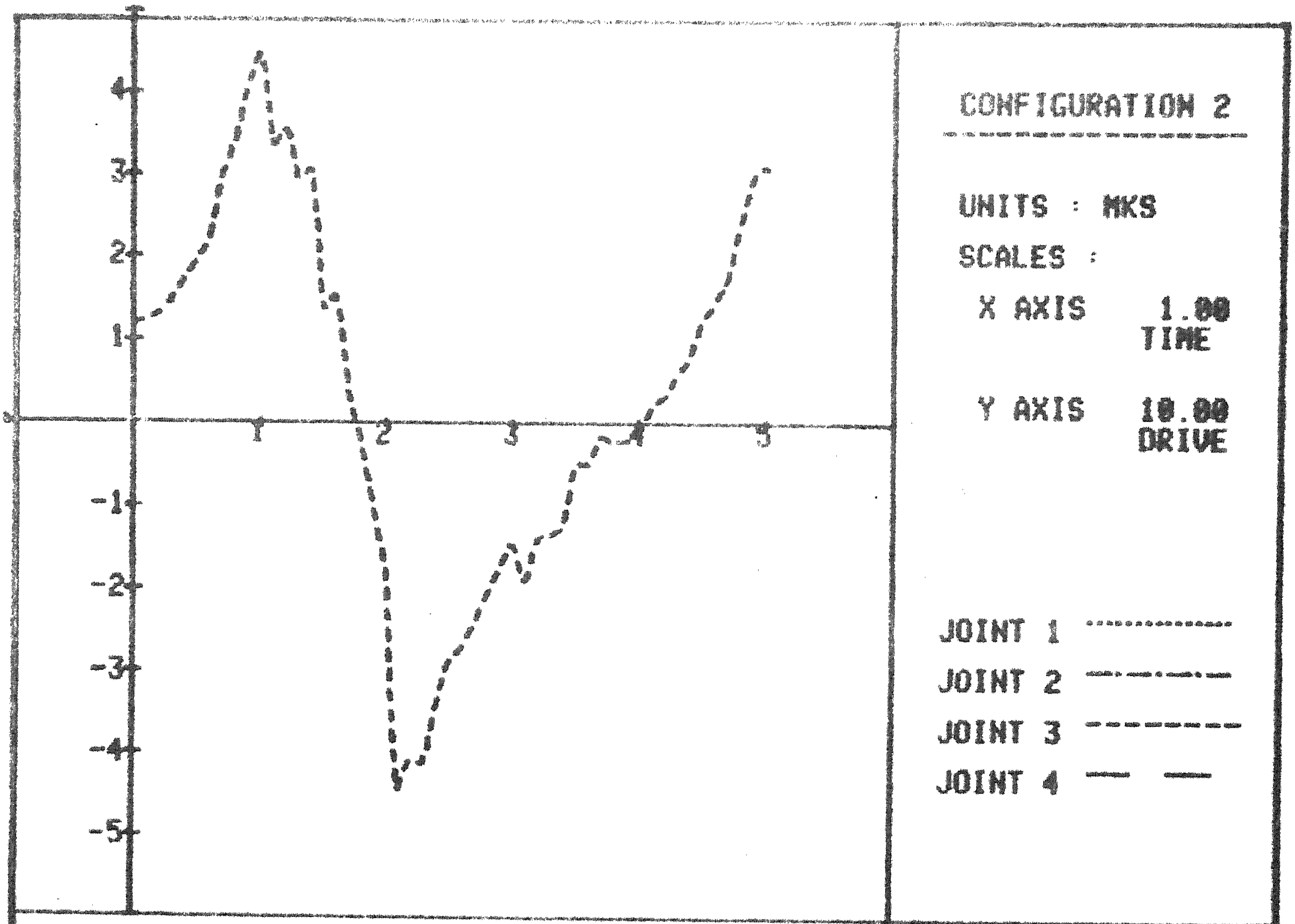

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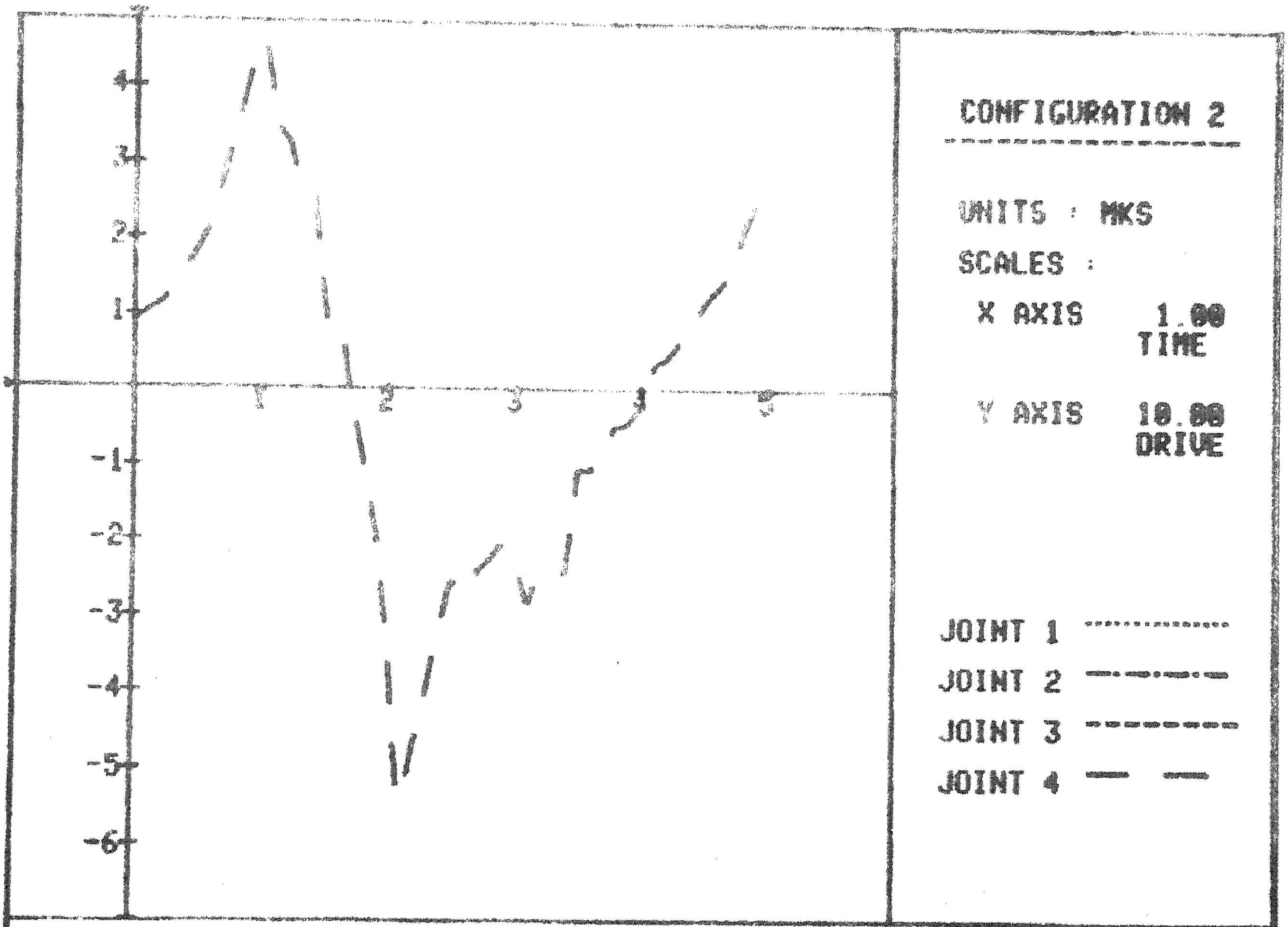
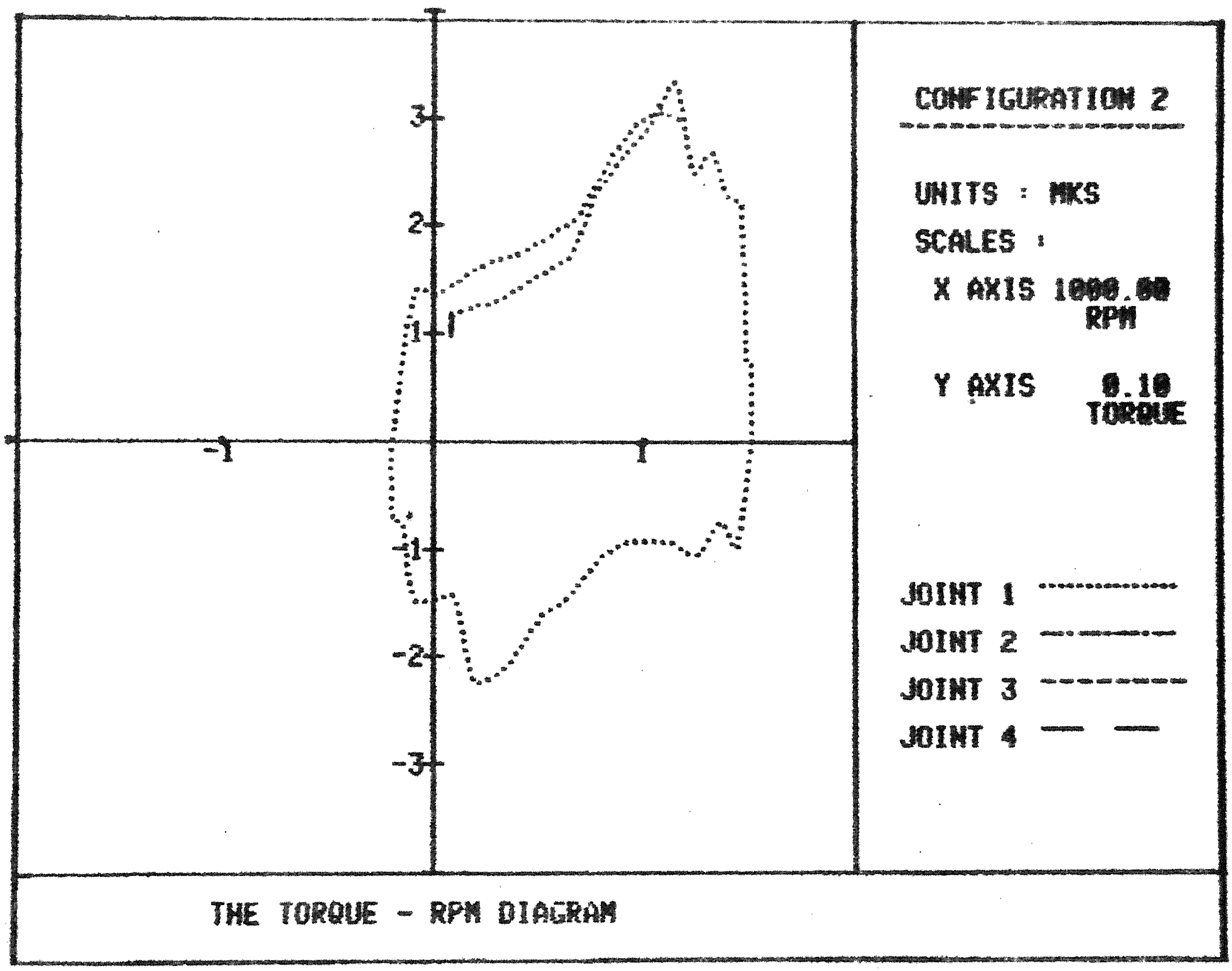
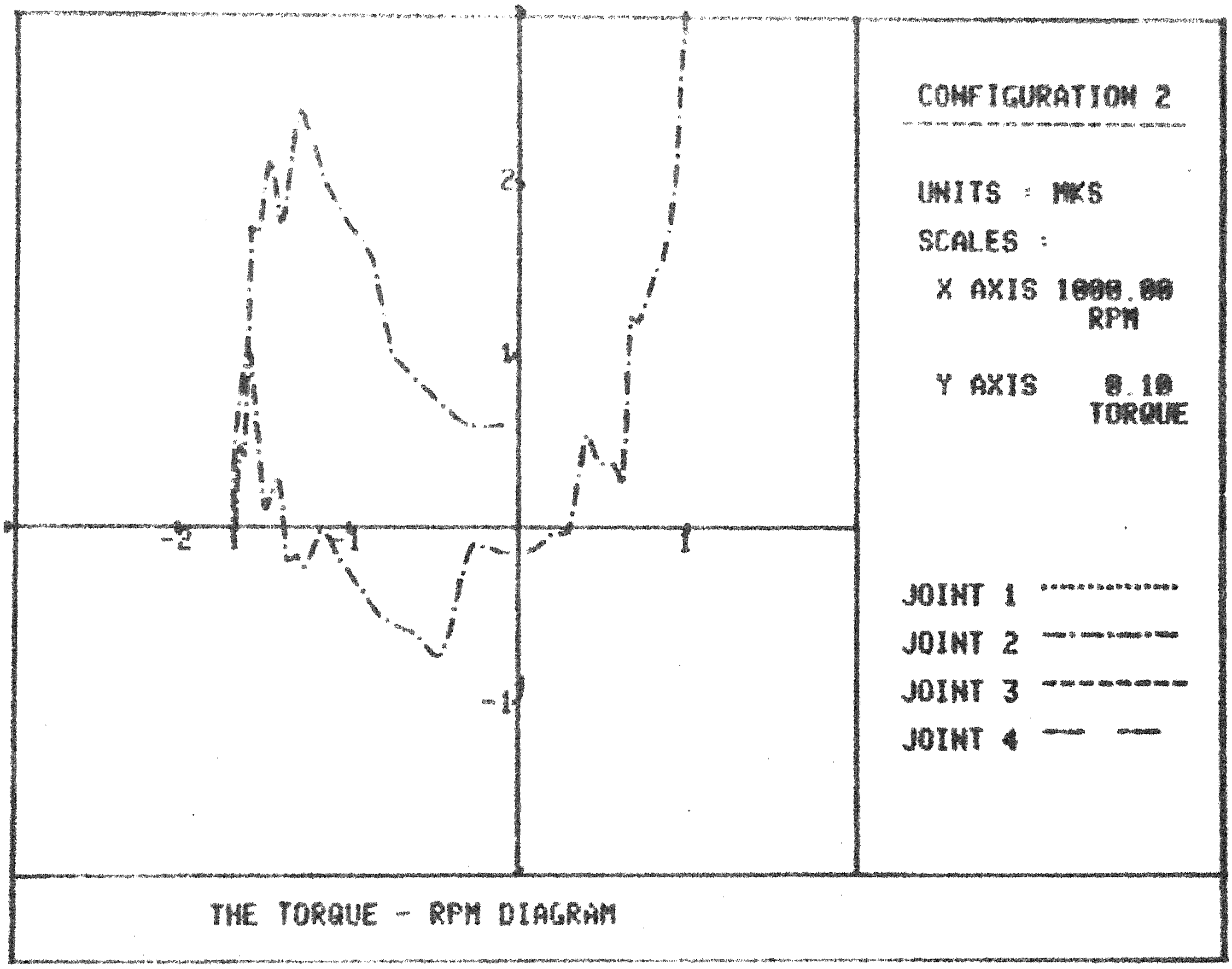
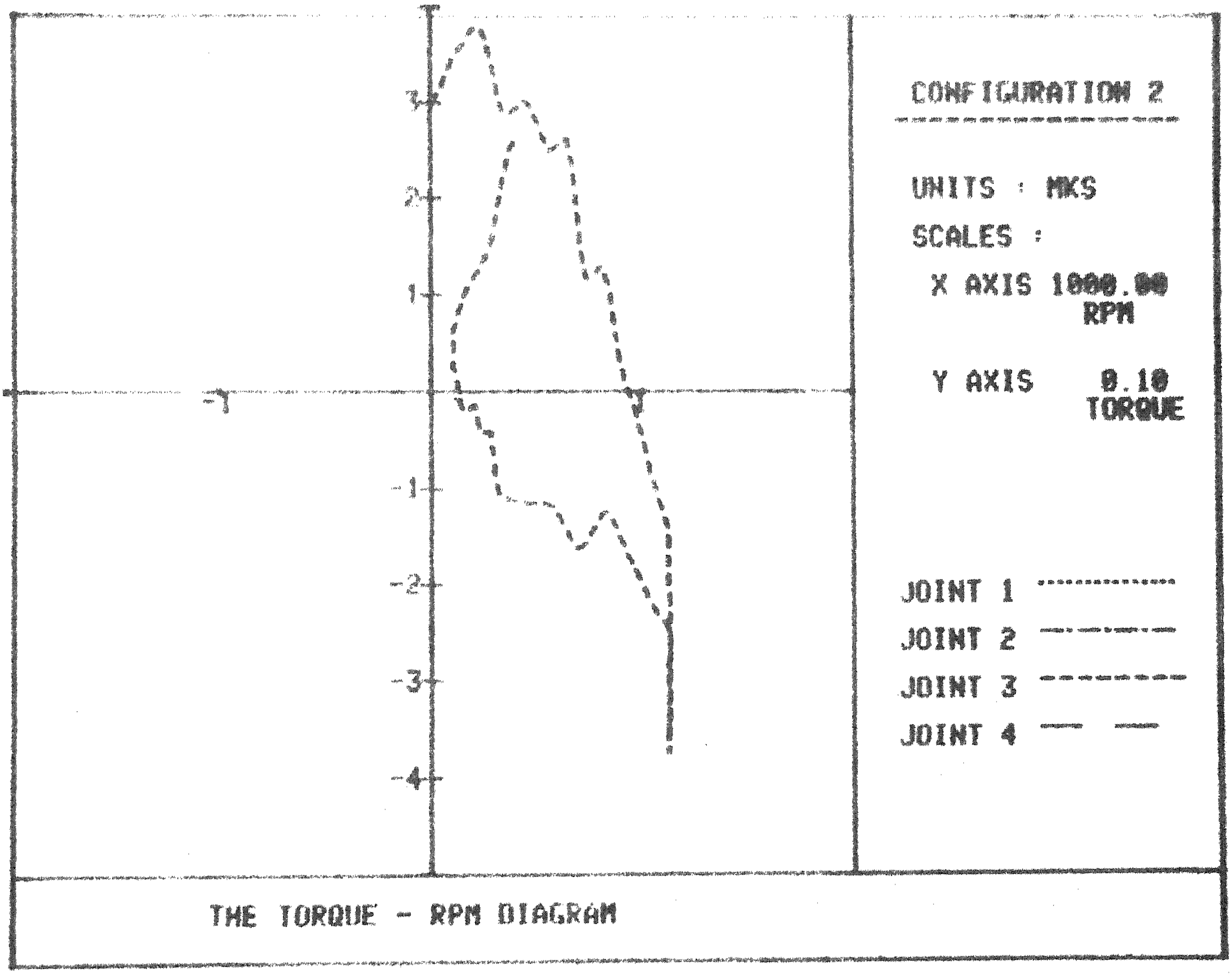


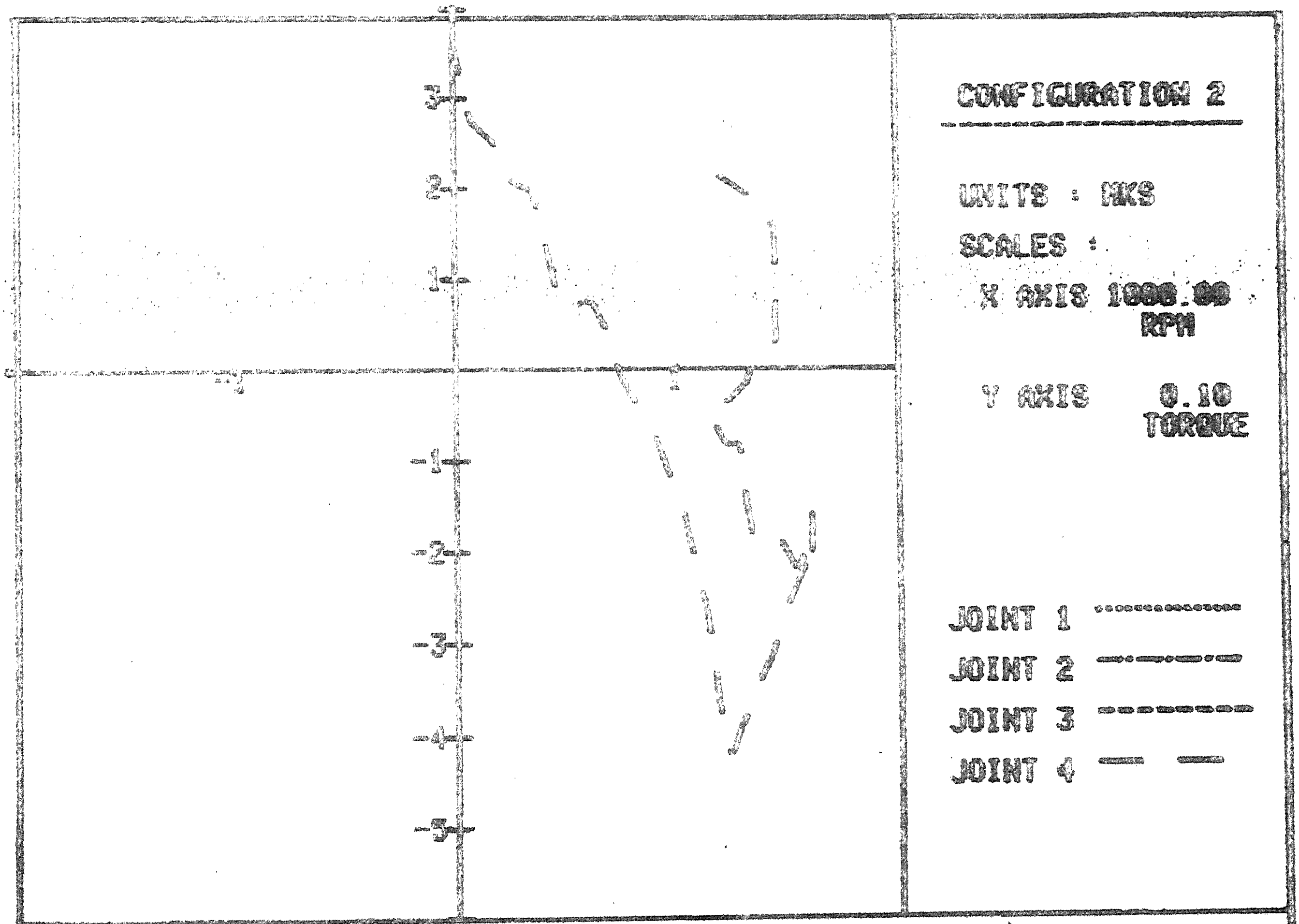
TIME HISTORY OF THE DRIVES


3
2
1
-1
-2
-3
-1
1
CONFIGURATION 2
UNITS : MKS
SCALES :
X AXIS 1000.00
RPM
Y AXIS 0.10
TORQUE
JOINT 1
JOINT 2
JOINT 3
JOINT 4
THE TORQUE - RPM DIAGRAM

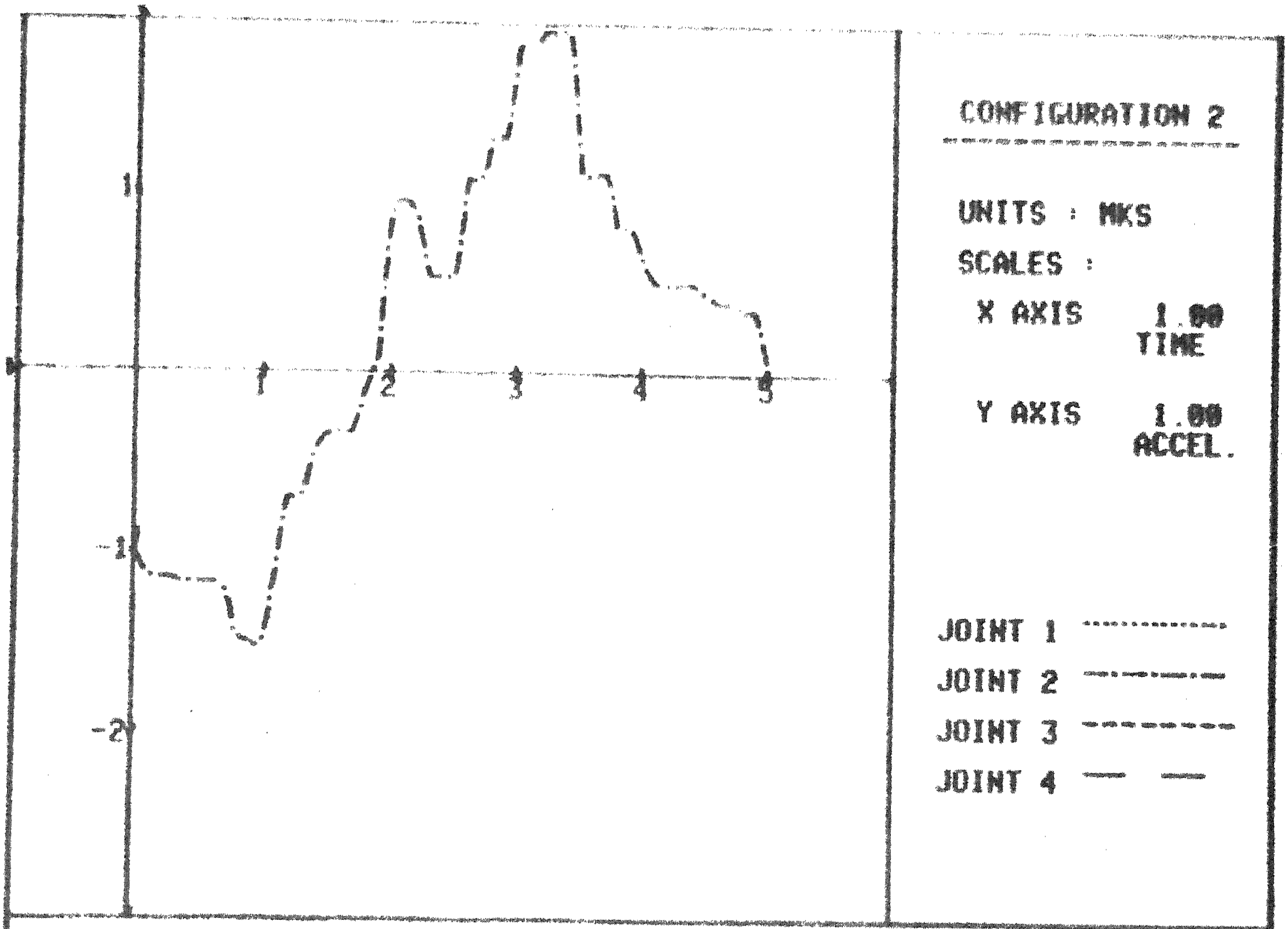


CONFIGURATION 2
UNITS : MKS
SCALES :
X AXIS 1000.00
RPM
Y AXIS 0.10
TORQUE
JOINT 1
JOINT 2
JOINT 3
JOINT 4
2
1
-1
-2
-1
1
THE TORQUE - RPM DIAGRAM

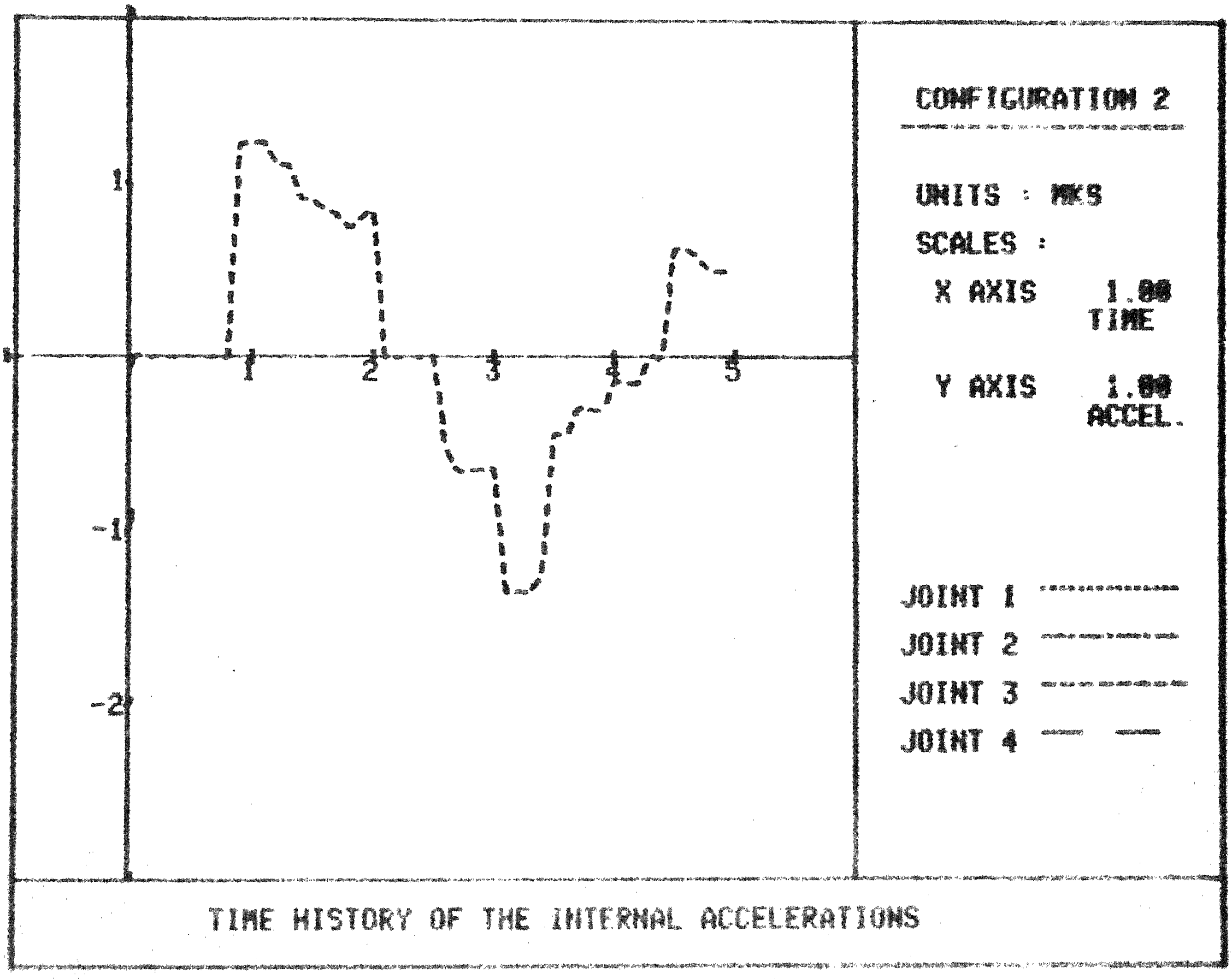

3
2
1
-1
-2
-3
-4
CONFIGURATION 2
UNITS : MKS
SCALES :
X AXIS 1000.00 RPM
Y AXIS 0.10 TORQUE
JOINT 1
JOINT 2
JOINT 3
JOINT 4
THE TORQUE - RPM DIAGRAM



THE TORQUE - RPM DIAGRAM



TIME HISTORY OF THE INTERNAL ACCELERATIONS



CONFIGURATION 2
UNITS : MKS
SCALES :
X AXIS 1.00 TIME
Y AXIS 1.00 ACCEL.
JOINT 1
JOINT 2
JOINT 3
JOINT 4
1
-1
-2
1
2
3
4
5
TIME HISTORY OF THE INTERNAL ACCELERATIONS